Preparing for an Uncertain Climate—Vol. I

October 1993

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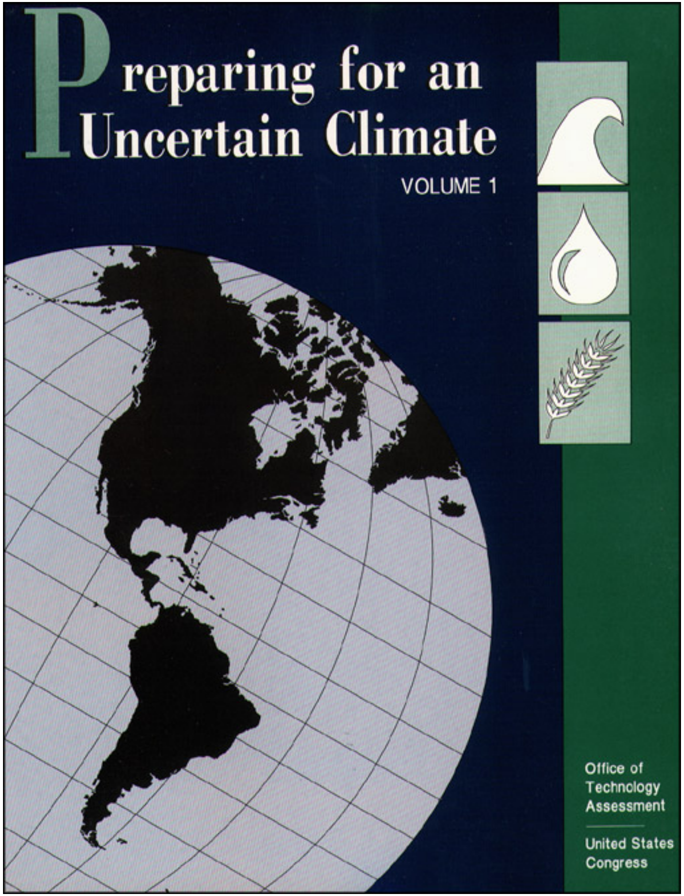

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Foreword

Preparing for an Uncertain Climate is OTA'S second report on climate change. In 1991, we published *Changing by Degrees: Steps to Reduce Greenhouse Gases,* which focused on ways to reduce the buildup of greenhouse gases in the atmosphere. Slowing the rate of growth in these emissions continues to be very important, but most analyses conclude that despite international efforts, the Earth is likely to warm several degrees over the next century.

Climate change poses many potential problems for human and natural systems, and the long-term effects of climate change on these systems are becoming increasingly important in public policy. For example, international agreements were recently signed on both climate change and biodiversity. Recognizing the potential problems, Congress asked OTA to examine how the Nation can best prepare for an uncertain future climate. This assessment tackles the difficult tasks of assessing how natural and human systems maybe affected by climate change and of evaluating the tools at our disposal to ease adaptation to a warmer climate. Volume 1 addresses coastal areas, water resources, and agriculture; volume 2 includes wetlands, preserved lands, and forests.

OTA identifies more than 100 options in the full report that could help ease the transition to an uncertain climate. We categorized a subset of these options as 'first steps. Options that fall into this group are near-term concerns because they will take a long time to complete, address 'front-line" or urgent issues that need attention first in order to make better decisions later, can be approached through efforts already under way, are beneficial for reasons other than helping to prepare for climate change, or represent near-term 'targets of opportunity."

The United States has put in place an ambitious Global Change Research Program to "observe, understand, and ultimately predict global and regional climate change. " This effort, which has so far been based overwhelmingly in the physical sciences, is not geared to help make natural resource planning and management decisions, to identify ecosystem-level responses to climate change, or to readily provide policy guidance on mitigation or adaptation. While scientists continue to reduce uncertainty, policy makers will continue to reauthorize environmental legislation, manage natural resources, and develop energy policy. Having mechanisms for integrating research and evaluating reasonable policy routes while we are completing the science would be a valuable addition to the Federal effort. This assessment could help guide these needed improvements.

Preparing for an Uncertain Climate was requested by three congressional committees: the Senate Committees on Environment and Public Works and on Commerce, Science, and Transportation, and the House Committee on Science, Space, and Technology. OTA appreciates the support this effort received from hundreds of contributors. Workshop participants, reviewers, contractors, and informal advisors gave us invaluable support as we attempted to sift through the voluminous material on this subject. OTA, however, remains solely responsible for the contents of this report.

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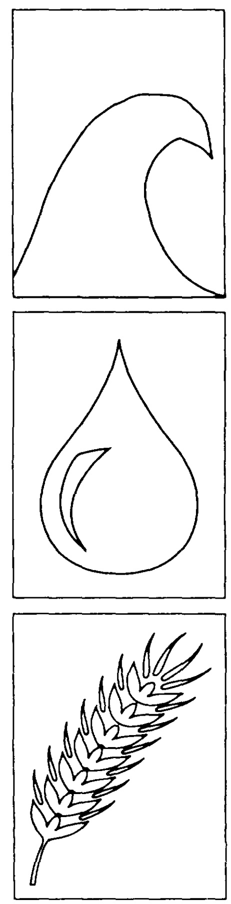
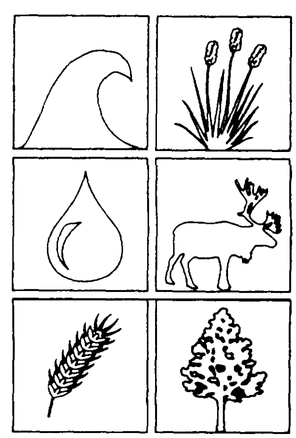


Synthesis, Summary and Policy Options 1

Widespread public attention to the question of whether or not climate is changing intensified during the hot summers of the late 1980s. Since then, during the time the Office of Technology Assessment (OTA) was conducting this assessment, the Nation has experienced major drought in the western and southeastern United States, powerful hurricanes in Florida and Hawaii, a destructive forest fire in Northern California, and substantial flooding in the Midwest. Although none of these events can be clearly linked to climate change, they represent the types of extreme events that may occur with greater frequency if climate warms.

Most scientists believe that the Earth's climate is likely to warm by several degrees during the next few decades. Although our understanding of climate change has progressed a great deal in the past few years, major knowledge gaps remain, and empirical evidence of human-induced climate change is not unequivocal. Many factors important to understanding climate, such as the role of clouds, ocean circulation, and solar cycles and the interactions between living organisms and the environment, cannot yet be reliably incorporated into general circulation models (GCMS), science-based computer models used to predict potential changes in average global surface temperature. Some key information that could guide policy response is likely to remain unknown for another decade or two (69). We cannot predict rates or magnitudes of changes in local or regional temperature and precipitation patterns. Predicting changes in the variability of climate and weather patterns, particularly on small spatial scales, is also beyond current scientific capabilities, Existing ecological, social, and economic models are similarly limited and cannot adequately predict the responses to climate



changes by natural systems (e.g., forests and wetlands) or managed systems (e.g., water resource systems and agriculture). Therefore, most policy decisions made in the near future about how to respond to the specter of climate change will be made in light of great uncertainty about the nature and magnitude of potential effects.

Although climate change has certainly become a public and scientific concern, what to do about it is not clear. Issues now being heatedly debated are the technical feasibility and economic implications of reducing or offsetting emissions of greenhouse gases. Several studies concluded that cutting U.S. emissions of carbon dioxide ($C0_2$), the most important anthropogenic greenhouse gas, below current levels is plausible. OTA'S 1991 report, *Changing by Degrees: Steps to Reduce Greenhouse Gases,* concluded that by adopting a package of low-cost measures, the United States could significantly slow the growth of its $C0_2$ emissions over the next 25 years-but could not easily decrease them to below current levels (172). With aggressive-but potentially expensive-initiatives, OTA found that the United States might be able to decrease its $C0_2$ emissions to 35 percent below today's levels by 2015. Even in this case, U.S. emissions of $C0_2$ are expected to rise again after 2015 unless there are successful programs for developing alternatives to fossil-energy supplies (such as solar and nuclear power)-programs that would lead to substantial increases in market penetration of one or more of these energy alternatives by 2015.

Since the 1992 United Nations Conference on Environment and Development (UNCED) in Brazil, many countries have signed the Climate Convention, seeking to freeze greenhouse gas emissions at 1990 levels in the near future. On Earth Day 1993, President Clinton announced that the United States would participate in this effort. The Climate Convention represents a landmark agreement and recognition that global environmental problems must be addressed on a global scale.

Nonetheless, the bulk of scientific evidence indicates that simply freezing greenhouse gas emissions at 1990 levels will not stop global warming. *Stabilizing emissions* is different from *stabilizing atmospheric concentrations.* Constant annual emissions will still increase the total concentration of greenhouse gases and, thus, the heat-trapping capacity of the atmosphere. The Intergovernmental Panel on Climate Change (WCC), an international group representing more than 50 countries, concluded that to stabilize the concentrations of greenhouse gases in the atmosphere at today's levels would require up to an 80 percent reduction in world $C0_2$ emission levels immediately, along with significant reductions in other greenhouse gases. Even if such reductions could be achieved, the world would warm about 1 to 4 OF (1 to 2 'C) because of long-lived greenhouse gases emitted over the last century. Given the virtual certainty that energy use (and associated $C0_2$ emissions) in developing countries will rise as they pursue economic growth and given the intense debate in the United States and other industrialized countries about the feasibility of achieving even a freeze in emissions, it seems certain that global atmospheric concentrations of greenhouse gases will continue to rise. Thus, unless the predictive GCMS are seriously flawed, average global temperatures are expected to increase several degrees over the next century, even under the most optimistic emissions scenarios (see box 2-B).[1]

If climate change is inevitable, then so is adaptation to climate change. Society and nature may have to cope with rising sea levels, more frequent drought and periods of temperature extremes, changes in water supplies, disruption of ecosystems, and changes in many other climate-sensitive natural resources (see ch. 2). The term *adaptation, as* used here, means any adjustment to

[1] All chapters, boxes, figures, and tables cited here can be found in volumes 1 and 2 of this report Volume 1 addresses coastal areas, water resources, and agriculture; volume 2 includes wetlands, preserved lands, and forests.

altered conditions; it can be a biological, technical, institutional, regulatory, behavioral, or economic response. It encompasses *passive adjustments (e.g.,* biologically *driven* changes in plant communities or gradual changes in human behavior and tastes), *deliberate reactive responses* (management responses after climate change effects are observed), and *anticipatory actions, (planning,* engineering, or regulatory responses taken in preparation for climate change). Throughout this report, we examine the ability of natural-resource-based systems, both unmanaged and managed, to adapt to climate change and consider means by which adaptation can be enhanced by modifying management, advancing research and technology, disseminating information, and taking legislative actions.

Given the current inability to predict accurately where, when, and how much change will occur, decisionmakers must plan for natural and managed systems in light of considerable uncertainty. It is understandable, under these circumstances, that postponing responses until more is known about climate change is very appealing. Nonetheless, uncertainty does not mean that the Nation cannot position itself better to cope with the broad range of impacts possible under climate change or protect itself against potentially costly future outcomes. In fact, delay in responding may leave the Nation poorly prepared to deal with the changes that do occur and may increase the possibility of impacts that are irreversible or otherwise very costly. Many options that will increase the Nation's ability to cope with the Uncertainties of climate change will also help in dealing with existing threats to natural resource systems, such as those related to climate extremes (e.g., droughts, floods, and fire) and the fragmentation of natural habitat.

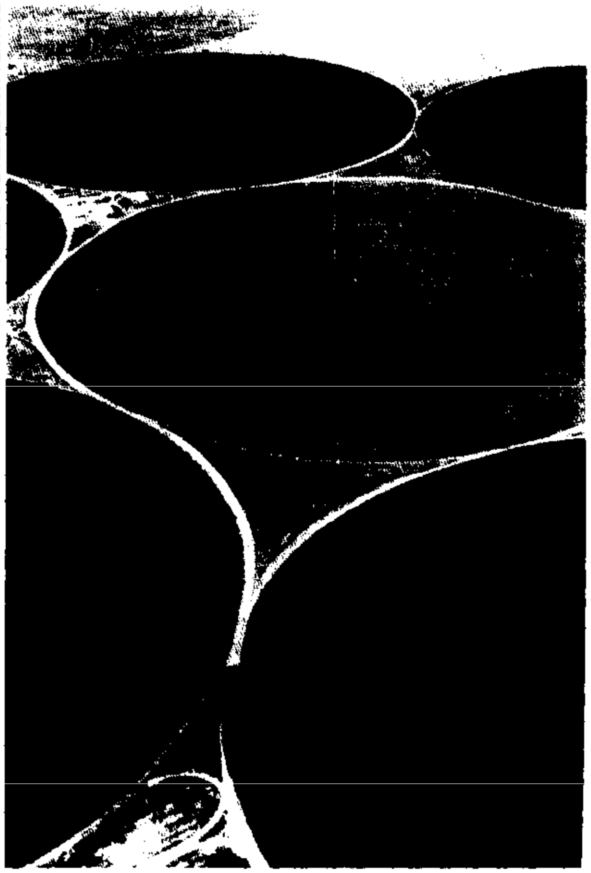
The following sections of this chapter discuss the OTA assessment, general problems posed by climate change, criteria for choosing strategic responses, near-term opportunities for Congressional action, and summaries and first steps for the six resource systems studied in detail.

THE OTA ASSESSMENT

Three Committees of Congress asked OTA to help them think about coping with potential climate change. OTA was asked: How can the United States set prudent policy, given that we do not know for certain what the climate will be? This assessment attempts to answer three key questions:

- What is at risk over what time frames? Which natural ecological systems and managed natural resource systems are at risk from climate change? How do the lead times needed for human interventions in these systems vary?
- How can we best plan for an uncertain climate? When and how should decisionmakers consider the uncertain effects of a changing climate as they plan the future management of natural and managed systems in the United States? What criteria should be used?
- Will we have answers when we need them? Does the current U.S. Global Change Research Program (USGCRP) reflect the short- and long-term needs of decisionmakers? Will it provide information about rates of climate change, the potential for "surprise' effects on different systems, potential strategies for making systems more resilient in the face of uncertain climate change, and adapting to the changes that may occur?

Society depends on natural and managed systems for both basic needs and amenities. These include, for example, food, shelter, clothing, drinking water, energy, and recreation. Many social and economic problems arise when the availability and diversity of goods and services decline. Such disruptions can range from mild to severe, and they include unemployment, famine, migration of workers, and political instability. Climate change heightens the uncertainty about future availability of desired goods and services.


USDA AGRICULTURAL RESEARCH SERVICE

In the West, center-pivot sprinklers irrigate wheat, alfalfa, potatoes, and other crops. Increasingly efficient irrigation techniques maybe critical if regional climates become drier.

Yet, given the potentially long delays until the onset of significant changes, reacting to climate change as it occurs may seem more practical than undertaking anticipatory measures. Why adopt a policy today to adapt to a climate change that may not occur, for which there is significant uncertainty about regional impacts, and for which benefits of the anticipatory measure may not be seen for decades? Effort put into adopting the measure could well be wasted. Furthermore, future generations may have more sophisticated technologies and greater wealth that can be used for adaptation (91).

The Committee on Science, Engineering, and Public Policy (COSEPUP) (27)[2] concluded that it is theoretically possible to put technology and practices into place to adjust to the changing climate as it happens if the change is gradual enough. However, the rate of climate change is, admittedly, unknown. IPCC concluded: "it is uncertain whether these changes-should they come-would be gradual or sudden" (68). Furthermore, "our imperfect understanding of climate processes . . . could make us vulnerable to surprises; just as the human-made ozone hole over Antarctica was entirely unpredicted" (69).

Waiting to react to climate change may be unsatisfactory if it is possible that climate change impacts will be very costly. Of greatest concern may be those systems where there is the possibility of surprise-of facing the potential for high costs without time to react--or where the climate change impacts will be irreversible. Such impacts seem more likely if long-lived structures or slow-to-adapt natural systems are affected, if adaptive measures require time to devise or implement, or if current trends and actions make adaptation less likely to succeed or more costly in the future. In these cases, anticipating climate change by taking steps now to smooth the path of adaptation may be appropriate.

Ideally, a policy-relevant research program could help identify appropriate actions as the current state of knowledge evolves. In response to the potential risks of climate change and the uncertainties surrounding the science, the Federal Government launched a massive, multiagency research effort in 1989 to monitor, understand,

2 COSEPUP's 1992 report, a joint publication of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine, stated: "While inventions and their adoption may occur quickly, we must ask whether the broad spectrum of current capital investments could be changed faat enough to match a change in climate in 50 to 100 years' (27). The report goes on to note that half a century should be time enough to allow most major technological systems (and some natural systems) to be transformed and most capital stock to turn over.

and, ultimately, predict global changes and to determine the mechanisms influencing these changes *(25, 26).* Chapter 3 examines the USGCRP and suggests ways to effectively broaden the program to both incorporate natural resource concerns and assessment activities.

Other studies have examined systems at risk from climate change in various ways (see boxes l-A, l-B, and 2-F and refs. 27, 67, and 188). To complement these analyses, OTA focused its examination of adaptation potential on areas where:

- Costs of climate change may be very high. For example, flood and wind damages from more-intense storms could lead to death and extensive property damage.
- Impacts of climate change may be irreversible. For example, species extinction and loss of valuable ecosystems—in wetlands, forests, and wilderness areas-may be permanent.
- The validity of long-term decisions made today will be affected by climate change. For example, trees planted with a life expectancy of many decades may not survive to maturity if climate conditions change. Agricultural and coastal development in climate-sensitive areas may add to the likelihood of future losses to natural disasters.
- Preparing for catastrophic events is already warranted. Reacting to climate change may mean reacting to climate extremes-such as floods, droughts, storms, and fires. Coordinated contingency planning can help avert high costs and reduce risk of loss.
- There is a significant Federal role in the research, planning, or management of these systems.

On the basis of these criteria, OTA selected six systems for further analysis:

1. coastal areas,
2. water resources,
3. agriculture,
4. wetlands,
5. preserves (federally protected natural areas), and
6. forests.

The first three systems are managed natural-resource-based systems with a high degree of government involvement and a complex system of incentives and subsidies in place; these are grouped together in volume 1 of the report. The other three systems include less-managed natural systems and are presented together in volume 2. Both volumes contain this summary chapter, a primer on climate change, and a chapter on the Federal research effort. Box 1-A highlights our overall methodological approach.

Each of the six systems OTA examined is stressed to some degree today, and that may influence how well it can respond to any change in the future. For example, because populations in coastal areas are growing, the exposure to costly natural disasters is increasing. Water scarcity and water-quality concerns are already common in many parts of the United States. Current agricultural support programs often distort and constrain choices about crop and farm management. Wetland loss continues-albeit at a much slower rate than 20 years ago-despite a stated national goal of "no net loss" (see vol. 2, ch. 4). Preserved natural areas serve aesthetic, recreational, and biodiversity functions, but may not be adequate in size or distribution to maintain wildlife and plant species in the face of growing habitat loss and fragmentation. U.S. forest managers are finding it increasingly difficult to meet the sometimes competing demands for recreation, environmental services, and commercial wood products.

Water is an integral element of all of the resource systems discussed in this report. Its abundance, location, and seasonal distribution are closely linked to climate, and this link has had much to do with where cities have flourished, how agriculture has developed, and what flora and fauna inhabit a region. Water quality and quantity will remain key to the economy. Future

Box I-A—The OTA Study in Context

Within the past 5 years, three major studies of the impacts of climate change have been released. The Environmental Protection Agency (EPA) (166) and the Committee on Science, Engineering, and Public Policy (COSEPUP) (27) issued reports on potential effects of global climate change on the United States; Working Group II of the Intergovernmental Panel on Climate Change (IPCC) focused on potential impacts from climate change worldwide (67).

The Sensitivity and Adaptability of Human Activities and Nature

Human activity and nature	Low sensitivity	Sensitive; adaptation at some cost	Sensitive; adaptation problematic
Industry and energy	✓		
Health	✓		
Farming		✓	
Managed forests and grasslands		✓	
Water resources		✓	
Tourism and recreation		✓	
Settlement and coastal structures		✓	
Human migration		✓	
Political tranquility		✓	
Natural landscapes			✓
Marine ecosystems			✓

SOURCE: Redrawn from Committee on Science, Engineering, and Public Policy, Panel on Policy Implications of Greenhouse Warming, National Academy of Sciences, National Academy of Engineering, and Institute for Medicine, Policy Implications of ***Greenhouse Warming: Mitigation, Adaptation, and the Science Base*** (Washington, DC: National Academy Press, 1992).

COSEPUP divided human activities and natural systems into three classes of sensitivity and adaptability to climate change: 1) low sensitivity, 2) sensitive but can adapt at a cost and 3) sensitive with problematic adjustment or adaptation (see table). The report concluded that industry decisionmaking horizons and building schedules are shorter than the time frame within which most climatic changes would emerge, so most industries could be expected to adapt as climate shifts. COSEPUP listed human migration and water resources as "sensitive to climate change," but adaptable "at some cost." Finally, it suggested that unmanaged natural ecosystems respond relatively slowly and that their ability to adapt to climate change is more questionable and "problematic" than that of managed cropland or timberland. The EPA report concluded that natural ecosystems have only limited ability to adapt if the climate changes rapidly and suggested that "managed systems may show more resilience."

The Office of Technology Assessment (OTA) analysis began with the EPA, COSEPUP, and IPCC reports and related literature, but it goes beyond them in several important ways. COSEPUP addressed natural systems primarily in the general terms of "natural landscape" and "marine ecosystems." However, natural systems are much more numerous and complex than this categorization suggests. We examine some natural systems in the United States at a much finer level of resolution (e.g., wetlands, forests, and preserved areas) and in different regions of the country.

We also consider systems under varying degrees of management intensity-from Iess-managed wilderness areas, wetlands, and some coastal systems, to systems managed for multiple uses, such as forests and rangelands, to intensively managed agricultural and commercial forestry systems. We consider each to be a system for which we can characterize outputs and' inputs. We focus on the outputs that society cares about whether for economic, recreational, aesthetic, or other reasons-in short, things about which policy is made.

While recognizing the value of climate predictions used in previous assessments, we chose to acknowledge the uncertainties of our changing climate by deliberately avoiding predictions linked to any particular climate change scenario. Instead, we examine the vulnerabilities of natural resource systems to climate change, attempt to elucidate how different climate variables drive natural resource systems, and examine the types of planning and management practices that might help vulnerable systems adapt to a changing climate.

Timing is key to our analyses. In addition to the sensitivity of systems to climate change, the lead time needed for human interventions in these systems also varies, as does the time framefor systems to respond. Continuation of the structure, function, and services of many systems in an uncertain future depends on decisions being made today. In this report, we highlight how today's decisions about long-lived systems (e.g., forests and water resource projects) may determine how those systems respond to tomorrow's unknown climate.

Finally, and perhaps most importantly for Congress, our assessment examines the institutions and legislative framework that surround natural and built systems in the United States today. Whether or not a system can adapt to a changing climate may depend on how adaptable the institutions themselves are. Many systems transcend agency, geographic, or legislative boundaries; such fragmentation can impede adaptation. OTA identifies these rigidities and offers new legislative, coordination, planning, and management options to facilitate adaptation.

water availability is essential for continued services and functions from coasts, water resources, agriculture, preserves, wetlands, and forests. Competition for water, whether for irrigation, recreation, wildlife, or urban use, is likely to heighten in some regions of the country. Throughout the report, we highlight this and other intersecting issues in cross-cutting boxes, indicated by a bar of icons representing the six systems studied (see table l-l).

THE PROBLEM OF CLIMATE CHANGE

Climate change alters the baseline against which future actions are gauged. Our lifestyles, water supplies, and food supplies and other things society values from natural resources rely on a dependable, consistent, and sustainable supply. Our institutions and infrastructure presume that the past is a reasonable surrogate for the future. When designing reservoirs, for example, historic rainfall patterns are assumed to provide a good indication of the range of future patterns. A farmer plants knowing that at times, weather conditions will cause a crop to fail, but with the expectation-based on past climate--that the crop will succeed, in most years.

Climate change poses two potential problems for existing management strategies for resources: 1) increased unpredictability resulting from changing climate averages, and 2) increased risk of surprises or large-scale losses. These, together with the "background" of increasing population, greater future demand, and growing competition for the use of scarce resources, make the need to improve the Nation's ability to deal with an uncertain climate all the more urgent.

Stresses on resources are most acute and visible during extreme events such as floods and droughts. Our response to such events has often proven to be expensive and unsatisfactory. Damages from the Mississippi River flooding in 1993 are expected to range from $5 billion to $10 billion, with Federal disaster payments of about $3 billion. Almost $4 billion in Federal payments went to farmers suffering crop losses during the 1988 drought. Hurricane Hugo cost the Federal Government about $1.6 billion. Hurricane Andrew topped $2 billion in Federal disaster payments, and many complained about the Government's response.[3] Policies that improve the Nation's ability to prepare for and cope more effectively with climate hazards (e.g., floods, fires, and droughts) would be valuable now **and** would help prepare the Nation for a less certain future.

3 Hurricane Andrew's estimated cost to property insurers as of February 1993 is at least $15.5 billion (136). Additional losses involved uninsured property, public utility equipment (e.g., power lines), crop damage, property insured under the National Flood Insurance and the Small Business Administration programs, lost tax revenue, and the costs of emergency services.

Table l-l—List of Boxes in Report[a]

■ What Is at Risk?

As described in chapter 2, climate change predicted by the models includes changes in precipitation patterns, increased temperature, in**creased** evaporation, and sea level rise. The combination of these factors could cause significant impacts on all systems. For example, sea level rise could lead to higher storm surges and

[a] Shading indicates boxes that discuss interactions across resource systems

increased erosion of coasts (see vol. 1, ch. 4). Shifts in precipitation patterns could cause more floods, droughts, water-supply disruptions, hydropower reductions, and groundwater overdrafts, especially in the arid West (see vol. 1, ch. 5). The ideal range for agricultural crops might move north as temperatures increase, and drought losses could become more frequent (see vol. 1, ch. 6). Forests could experience more-frequent fire and diebacks driven by drought, insects, and disease (see vol. 2, ch. 6). It could become difficult to retain unique assemblages of plants and animals in preserves as the climate to which they are adapted effectively shifts northward or to higher elevations (see vol. 2, ch. 5). With sea level rise, loss of coastal wetlands maybe accelerated, and regional drying could eliminate some prairie potholes (see vol. 2, ch. 4).

The loss of soil moisture that might result from higher evaporation rates at warmer temperatures is likely to present the greatest threat to natural systems. Figure 1-1 shows areas of the United States that may undergo significant changes in soil moisture based on climate changes projected by two GCMS. The Goddard Institute for Space Studies (GISS) scenario suggests that large areas face moderate drying. The Geophysical Fluid Dynamics Laboratory (GFDL) scenario shows more severe drying across much of the eastern and central United States. Figure 1-2 illustrates the

The summer floods of 1993 in the Midwest demonstrate the risks of floodplain development combined with intensive control of river flow. The satellite photograph on the top shows the Mississippi River as it appeared in July of 1988 during the drought; the one on the bottom shows the same area during the floods of July 1993.

extent to which changes in soil moisture could affect U.S. lands in natural cover (e.g., forests and wetlands) or agricultural use. Much of the Nation's natural resource base may face at least moderate drying, which is likely to increase stress on vegetation.

It is impossible to estimate with any confidence the cost of climate change to society. Estimates of the costs to the United States resulting from an average temperature increase of 4 to 5 OF (2 to 3°C)[4] range from 0.3 to 2.0 percent of the gross national product (GNP) (22, 23)-corresponding to tens of billions of dollars per year. Box 1-B highlights a broad range of climate impacts that could be caused by climate change.

Although it is desirable to anticipate climate change, the uncertainties involved make the design of appropriate policies challenging. These uncertainties include: 1) the extent of global and regional climate change, 2) its economic and ecological impacts, and 3) the ability of society to adapt.

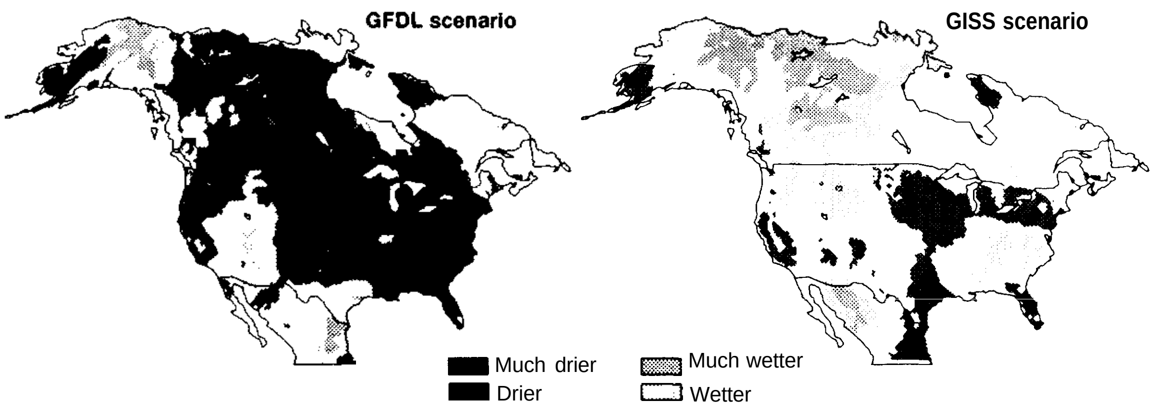
Uncertainties About Global and Regional Climate Change

Atmospheric scientists generally agree about the direction of climate change on a global and latitudinal scale. Global temperatures will likely rise, which would cause an increase in global precipitation and sea levels. Temperature increases are likely to be greater at higher latitudes. Winter precipitation could increase in middle and high latitudes; decreased summer precipitation in midcontinental, midlatitude regions could result in reduced summer soil moisture (69). At finer spatial scales, such as at the regional or State level, uncertainty about climate change increases.

The rate of change is also uncertain. IPCC estimated that global average temperatures will increase at over 0.5 OF (0.3°C) per decade. As average temperatures increase, the entire range of expected temperatures increases as well; thus, both the warmest and coolest temperatures experienced will be warmer than before. This does not preclude late frosts or early freezes if variability increases. Some analyses show that climate variability may increase at the regional level-a series of warm years in a region could be followed by a series of cool years (195). There is, however, significant uncertainty about whether the frequency and intensity of extreme events will change. It is likely that, on average, precipitation worldwide will increase with climate change (69), but the models suggest that the interior of continents will get drier. It is not known whether droughts or floods will increase or decrease.

[4] This temperature increase is the estimated equilibrium warming from an atmosphere containing a greenhouse gas concentration equivalent to a doubling of CO_2 above preindustrial levels. Although the atmospheric concentration of gases leading to this temperature change is expected by about 2030, due to time lags, any resulting temperature effect might not be fully realized until several decades later.

Figure I-I—Potential Sol I-Moisture Changes Under Two GCM Climate Change Scenarios



NOTE: GFDL=Geophysical Fluid Dynamics Laboratory; GISS--Goddard Institute for Space Studies.

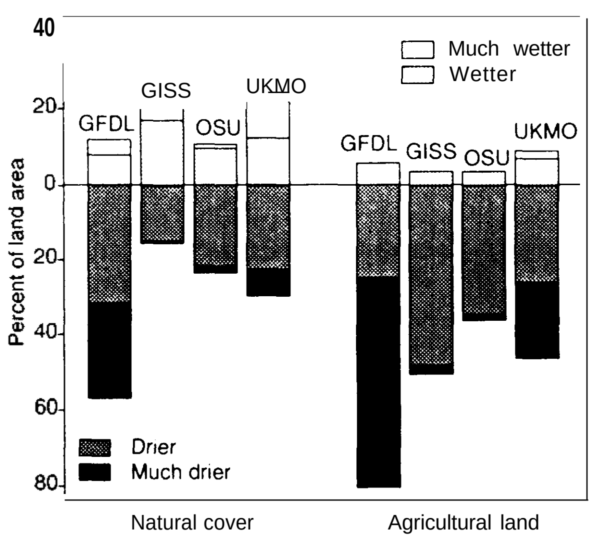
SOURCE: P.N. Halpin, 'Ecosysatems at Risk to Potential Climate Change," contractor report prepared for the Office of Technology Assessment, June 1993.

Some analyses predict that hurricane intensities could increase (43), and drought in lower latitudes could be more severe (144).

▌Uncertainties About Direct Effects

Even if the regional changes in climate could be predicted, important uncertainties would remain about the physical and biological effects they would have. We do not really know how vegetation,animals, and other natural resources will be affected by climate change. Rising concentrations of atmospheric CO_2 will change the rates at which plants grow, respire, use water, and set seeds. Numerous laboratory experiments on intensively managed agricultural systems suggest that CO_2 will boost plant growth and productivity as long as other nutrients are plentiful (6, 39, 81); this is called the CO_2 *fertilization effect (see* **ch.** *2). This* **effect has not yet been studied in many natural ecosystems (72, 124). Many studies of climate effects have used statistical models that relate natural vegetation or crop productivity to differences in current regional climates in order to estimate impacts under climate change scenarios. These are summarized in chapter 2 and in volume 1, chapter 6. The ability of plants and animals to**

Figure 1-2-Soil-Moisture Changes for Agricultural Lands and Areas of Natural Cover, by GCM Climate Change Scenario



NOTE: Bars above the zero axis show the percent of land area becoming wetter; bars below the axis show the percent of land area becoming drier. GFDL--Geophysical fluid Dynamics Laboratory; GISS-Goddard Institute for Space studies; OSU-Oregon State University; and UKMO-United Kingdom Meteorological Office.

SOURCE: P.N. Halpin, "Ecosystems at Risk to Potential Climate Change," contractor report prepared for the Office of Technology Assessment, June 1993.

Box I-B-How Climate Change May Affect Various Systems[1]

Natural ecosystems-These may be the systems most vulnerable to climate change. We are least able to intervene and help with adaptation of natural ecosystems because of limited knowledge about ecological processes (see chs. 2 and 3). The shift in climate zones may far exceed the ability of vegetation, such as forests, to adapt through migration (see fig. 1-7). Climate zones may shift hundreds of miles in a century, whereas natural rates of dispersal and colonization maybe on the order of tens of miles in the same time period (35). In addition, fire and disease could result in rapid dieback of many existing forests and other terrestrial ecosystems (157). Helping plants to migrate through such activities as widespread seed dispersal would be very expensive and have dubious prospects for success (188). These issues are discussed in detail in "Forests" (vol. 2, ch. 6).

Climate change could also lead to a loss of species diversity. Isolated ("island") species may find themselves in climate zones that are no longer suitable for their survival (132). The potential for migration of plants and animals to new suitable habitats is not known, but barriers such as water bodies or development could impede migration (see fig. 1-6), Species in mountainous terrain could migrate to higher elevations. This creates reduced habitat areas, which are correlated with reductions in species diversity. For example, a study ofa5'F (3 'C) warming in the Great Basin National Park in eastern Nevada concluded that it would cause 20 to 50 percent of species in individual mountain ranges to go extinct (108). The ability for human intervention to maintain species diversity in the face of climate change is currently limited. Selected species could be transplanted to new habitats, but this could be very resource intensive and would only be feasible in certain cases; little research has actually been done on transplantation of multiple-species systems. Migration corridors could be created, but their chances of success are limited because migration rates are slow and the direction of species migration is unknown. In addition, the creation of corridors maybe relatively expensive compared with setting aside new protected areas (154). These issues are discussed further in "Preserves: Federally Protected Natural Areas" (vol. 2, ch. 5).

Climate change can result in the loss of coastal wetlands directly through sea level rise, and indirectly, through interaction with societal response to sea level rise. Many coastal wetlands will likely be inundated because the sea will rise faster than wetland sediments accrue (161). Some wetlands will adapt to climate change by migrating upland with the rising tides. The areas with the greatest risk of wetland loss are along the Gulf and East Coasts of the United States (see fig. 1 -4). This will result in a net loss of wetlands because vast areas of tidal flats, such as in the Mississippi Delta, will be inundated, while inland migration will create new wetlands having only a fraction of the area of today's wetlands.[2] This net loss of wetlands will be even larger where coastal structures, such as bulkheads or levees, block the inland migration of wetlands (162).

Even if it were feasible to create new coastal wetlands, the costs of this would be so high that large-scale restoration programs would become unattractive. The average cost of creating wetlands has been estimated at roughly $20,000 to $45,000 per acre ($50,000 to $100,000 per hectare),[3] not including land-acquisition costs.[4] This figure, however, can vary from just a few hundred dollars per acre to many hundreds of thousands of dollars per acre. Though technology is improving (see vol. 2, box 4-A), attempts to recreate wetland structure and function fully have been limited. Prohibiting the construction of or removing coastal structures would enable more wetlands to colonize upland areas. It may not be feasible to move some existing coastal structures that impede wetland migration. For example, it is unlikely that areas of dense development would be relocated.

1 This box is a compendium of information drawn from previous studies, recent research, and OTA'S assessment. The back chapters of this report discuss a subset of these issues.

2 S. Leatherman, University of Maryland at College Park, personal communication, November 1992.

3 To convert acres to hectares, multiply by 0.405.

4 D. King, Chesapeake Biological Laboratory, University of Maryland, personal communication, November 1992.

Prairie pothole and riparian wetlands in regions that get drier maybe at greater risk than those in regions that get wetter. For example, in the North central States, increases in temperatures and evaporation rates could cause many prairie potholes to shrink or disappear, leading to further declines in already diminished continental waterfowl populations (9). Tundra may shrink as increased temperatures allow the permafrost to thaw and drain (see box l-G). In addition, wetlands of any type that are already degraded by pollution, water diversions, or fragmentation may also be particularly vulnerable (1 98, 199). The status and vulnerability of coastal, riparian, depressional, and tundra wetlands are discussed in "Wetlands" (vol. 2, ch. 4).

Fisheries-The potential effects of climate change on aquatic ecosystems have been studied very little to date, and could vary significantly. in some cases, marine fish maybe able to migrate to new, more suitable habitats, depending on several factors, if food sources are available (80). Some freshwater fish in open waters, such as the Great Lakes, could benefit from a larger thermal niche (98). Fish in small lakes and streams, however, may suffer from increases in temperature that adversely affect survival, reproduction, or their ability to migrate to cooler locations (101). Changes in water quality will also affect the survival of aquatic organisms. Climate change may alter circulation patterns in many lakes, reducing dissolved-oxygen concentrations. Higher temperatures will also act to reduce dissolved-oxygen concentrations (71). Sea level rise will increase saltwater intrusion of estuaries, potentially benefiting marine fish at the expense of freshwater species (80). However, changes in estuaries could have broad impacts on the U.S. fishery. By far, the greatest portion of commercial catches, with the exception of those from Alaskan fisheries, are composed of estuarine-dependent species (139). Ongoing alterations of critical habitat (such as those caused by geographic fragmentation and pollution) may be exacerbated by climate change. Box 2-C (ch. 2) discusses, by region, the condition and value of fisheries today, current problems, and the potential impacts of climate change.

Agriculture--This system is very sensitive to climate, but climate change impacts maybe offset by intense management over short time frames. High temperatures and drought could reduce crop yields, although this effect could be counteracted by higher atmospheric concentrations of carbon dioxide and longer growing seasons in higher latitudes (129). The potential for agricultural adaptation, particularly at the farm level, is very high (30). Changes in management practices (e.g., changing planting dates or using irrigation or crop-switching) can reduce or eliminate many of the potentially negative impacts of climate change. Shifts in climate zones would result in changes in relative productivity levels, with some areas increasing output, and other areas reducing output due to increased competition (l). See "Agriculture" (vol. 1, ch. 6) for further discussion.

Coastal resources-Cities, roads, airports, and other coastal resources are vulnerable to flooding from sea level rise and hurricanes. The population near the coast is growing faster than populations in any other region of the country, and the construction of buildings and infrastructure to serve this growing population is proceeding rapidly. As a result, protection against and recovery from hazards peculiar to t he coastal zone, such as hurricanes and sea level rise, are becoming ever more costly (11). The combination of popularity and risk in coastal areas has important near-term consequences for the safety of coastal residents, protection of property, maintenance of local economies, and preservation of remaining natural areas. These points are discussed further in "Coasts" (vol. 1, ch. 4).

Water resources-These resources are vulnerable to several climate change impacts. Changes in precipitation and higher levels of evapotranspiration can combine to affect surface-water and groundwater supplies, flood and drought frequency, and hydropower production. Arid basins could experience the largest relative change in water flow from climate change (67). Numerous studies have been conducted on the relative vulnerability of the major US. river basins to flood and drought, supply disruptions, hydropower reductions, groundwater overdrafts, and extreme events (48, 49,88, 188). They conclude that the water resource regions most vulnerable to some or all of these events are the Great Basin, California, Missouri, Arkansas, Texas Gulf, Rio Grande, and Lower Colorado (see fig. 1-5). See "Water" (vol. 1, ch. 5) for more information; Appendix 5.1 lists State-by-State problems.

(Continued on next page)

Box I-B-How Climate Change May Affect Various Systems--(Continued)

Human health-Climate change could affect human health, but there is a great deal of uncertainty about whether mortality and morbidity would actually increase and about the potential for adaptive measures (such as the use of air conditioning) to offset any negative impacts. Several studies have concluded that the potential range of infectious diseases could shift with climate change, but the exact nature of these shifts is uncertain (94). Even if the range of disease-carrying vectors, such as mosquitoes, changes, enhanced pest-control measures could nullify the increased threat of disease. Effects of climate change in other countries could displace some populations. If "environmental refugees" lead to an increase in immigration, there is the potential for increased importation of communicable diseases into the United States (184). Other studies have shown that climate change could lead to increased cases of heat-stress mortality (74). Uncertainties about changes in human physiological and behavioral response make it difficult to draw conclusions about the risks of climate change to human health.

Energy-Higher temperatures will no doubt increase energy demand for cooling and decrease energy demand for heating. This would result in an increase in the demand for electricity (primarily for air conditioning) and for electric-generating capacity (93). This new demand would not be completely offset by reductions in the use of oil and gas for heating (98). The largest capital costs would be associated with increased power plant construction, which could cost as much as $170 to $320 billion, about 12 percent more than the increases in capacity needed to meet population and economic growth through the middle of the next century (93). As with sea level rise, adapting to increased energy demand could involve significant costs.

Transportation-Some forms of transportation could be positively or negatively affected by climate change. inland shipping may be the most sensitive to climate change. On the one hand, warmer winters would likely result in less ice cover and a longer shipping season. For example, ice cover on the Great Lakes could be reduced by 5 to 13 weeks (4), lowering shipping and related costs (78). On the other hand, lower river flow and lake levels could increase shipping costs by reducing shipping tonnage capacity or blocking shipping (143). Some roads near the coast may have to be moved or protected from sea level rise. In many instances, adaptation is highly probable in transportation at some cost to the economy (see vol. 1, box 5-E, "Navigating the Mississippi through Wet and Dry Times").

adapt to changes in climate, either through physiological adjustment or through migration, is uncertain. Historically, trees can disperse and migrate about 60 miles (100 kilometers)[5] per century, but the projected rates of temperature change would require migration rates 5 to 10 times faster for forests to remain in suitable habitats (35, 36). The success with which natural vegetation can migrate will depend on seed dispersal, physical barriers to migration (e.g., mountains and developed land), competition between species, and the availability of fertile soils in areas of suitable climate.

■ Uncertainties About Society's Ability to Adapt

Finally, how society will respond to whatever climate change occurs and the resulting impacts are uncertain. Coping with climate change can take the form of technical, institutional, regulatory, behavioral, and economic adjustments. Future technologies and levels of income are unknown, although they will most likely improve and increase and will aid in adaptation (5). Will population growth or environmental consensus limit or expand adaptation options? Will people

5 To convert miles to kilometers, multiply by 1.609.

Box 1-B-How Climate Change May Affect Various Systems--(Continued)

The table below summarizes potential climate change impacts for these various systems.

Potential Climate Change Impacts for Various Systems

Systems	Potential impacts
Forests/terrestrial vegetation	Migration of vegetation. Reduction in inhabited range. Altered ecosystem composition.
Species diversity	Loss of diversity. Migration of species. Invasion of new species.
Coastal wetlands	Inundation of wetlands. Migration of wetlands.
Aquatic ecosystems	Loss of habitat. Migration to new habitats, Invasion of new species.
Coastal resources	Inundation of coastal development. Increased risk of flooding.
Water resources	Changes in supplies. Changes in drought and floods. Changes in water quality and hydropower production.
Agriculture	Changes in crop yields. Shifts in relative productivity and production,
Human health	Shifts in range of infectious diseases. Changes in heat-stress and cold-weather afflictions,
Energy	Increase in cooling demand. Decrease in heating demand. Changes in hydropower output.
Transportation	Fewer disruptions of winter transportation. Increased risk for summer inland navigation. Risks to coastal roads.

SOURCE: J.B. Smith and J. Mueller-Vollmer, "Setting Priorities for Adapting to Climate Change," contractor paper prepared for the Office of Technology Assessment, March 1992.

react quickly and efficiently to trends deemed outside the range of normal, or will they assume that conditions will return to-historic no&? Will people overreact to periodic climate extremes that do not actually signal a substantial change in the underlying climate? Responses to recent extreme events, such as the Mississippi River flooding in the summer of 1993, may provide an interesting lesson.

CHOOSING ADAPTATION STRATEGIES

How should" decisionmakers incorporate the uncertainties posed by a changing climate into long-term plans for resource systems? What can be done to minimize vulnerability to climate change? Uncertainty makes acting now difficult, but it also makes preparing for a wide range and intensity of climate impacts essential.

The Grand Teton National Park, along with other national parks and preserves, provides habitat for countless species of birds and wildlife. The parks and preserves also offer extensive recreational opportunities such as hiking, camping, nature study, and photography. These are examples of services at risk from climate change.

Possible responses to the threat of climate change depend on what one wants to save. Do we try to maintain systems in their current form (e.g., the extent of forests and the varieties of crops), or do we maintain the services they provide (e.g., enough food for the population, scenic views, beach recreation facilities)? Do we wish to minimize the economic costs of facing a changing climate? Do we attempt to forestall only catastrophic events? However these interests are balanced, two general primary characteristics of adaptation policies stand out: *flexibility* and *robustness.* By helping to ensure quick and effective response to changing circumstances (flexibility) and by being prepared for the worst (robustness), the potential costs of an uncertain future climate can be reduced.

Just how much effort should be expended to avoid future risks will ultimately depend on the perceived costs of the effort compared with the likelihood and scale of future damages that will be avoided. In some cases, the same strategies that help protect against climate risks might also provide some immediate and certain benefits: enhanced services from natural systems, improved productivity in managed systems, better means for dealing with existing climate variability and weather extremes, or reduced environmental damages from managed systems. The costs of these *low-regrets* strategies or activities may be relatively easy to defend. Other activities, however, would be most useful only in the event of severe climate change. The costs of such activities may be considered in the same light in which we consider the purchase of insurance--it may be better to pay a relatively small premium now than to be uninsured against the threat of severe and more costly ecological and economic damage.

Enhancing Flexibility

Any policies that improve the chances of adapting more smoothly and painlessly provide a buffer against the negative impacts of climate change. Flexible systems and policies are those that allow self-adjustments or midcourse corrections as needed without major economic or social disruption. For example, flexible systems can be fine-tuned to cope with hot and dry weather as well as more-intense rainstorms. The system should work now, under current climate conditions. Flexibility would not preclude potentially desirable actions or lock policy makers into expensive, irreversible decisions. For example, in some cases, building a dam is a less flexible policy than is water conservation. If new information becomes available that suggests that the dam is not needed in that location or is the wrong size, fine-tuning is difficult. Efforts to conserve water can (within limits) be used to supply quantities of water without building new, expensive infrastructure with 50- to 100-year lifetimes; the policy is also reversible in times when water is plentiful (see vol. 1, boxes 5-G, 5-H, 5-I, and 5-J).

Advancing the knowledge base will enhance flexibility. In agriculture, the development of new crops suited to a wide variety of climates, improved understanding of the performance of crops under a changing climate, and continuing education and extension programs to provide better-informed decisionmaking by farmers will all help smooth the path of adaptation (see vol. 1, ch. 6). In general, research that clarifies how systems respond to climate change will help identify and expand the range of possible adaptive actions and will speed their successful implementation.

Removing legislative or administrative constraints that now limit our ability to change would also promote flexibility. For example, the complicated programs of price supports in agriculture now penalize farmers who choose to change planting or management practices significantly. Given the importance of agriculture in the United States, large economic costs could be associated with even brief delays in agricultural adjustment to a changing climate. Other subsidies, such as those for irrigation and those implicit in the support for infrastructure in coastal zones, add to our inflexibility by encouraging the development of built systems in areas that maybe increasingly at risk to natural disasters. Resolving conflicts over the use of natural resources, through the creation of organizational structures or market incentives, should also help with our ability to implement change.

■ Enhancing Robustness

Policies can also minimize the risk of adverse effects from climate change by making systems less sensitive to climate. Robust systems are those that can tolerate a wide range of climate conditions and are, therefore, less vulnerable to climate change extremes. Actions that increase robustness in a system are those that help protect against the threat of large-scale losses or climate surprises. The robustness of a system can be increased in several ways. One is to take actions that make the system itself inherently more tolerant of a variety of climate conditions. For example, developing and planting crops that perform reasonably well under a wide range of climates may be wise no matter how the climate changes. Adding capacity to dams or other structures can make them more "robust, ' that is, able to accommodate greater variability in precipitation. Another way to increase robustness is to put a variety of mechanisms in place to protect against possible losses, hoping that some mechanisms will succeed even if others fail. For example, a mix of management strategies for forests and natural areas could be used to protect against climate change.

Improving the robustness of a system will often require an *insurance strategy something* must be initiated now in order to avoid extremely high costs under a much warmer climate. The idea is that paying a small amount now will reduce the risks of a major loss in the future. For example, establishing gene banks or learning how to undertake ecosystem restoration may be an "investment' that would reduce the risks of catastrophic forest or ecosystem loss in the future.

Efforts that enhance the general health, productivity, or quality of a system can also enhance robustness by making the system more resilient, or able to tolerate some climate-related stresses. Actions promoting robustness include improving the quality and protection of wetlands, minimizing existing threats to natural areas, and establishing new preserves (see vol. 2, chs. 4 and 5). Planning and management measures that avert trends that make adaptation more difficult in the future are also robust strategies.

It is not immediately obvious that natural systems, such as forests or wetlands, are less robust (more vulnerable) in the short term than are managed systems such as agriculture and water-supply systems. Natural systems do have some inherent buffering to protect themselves against existing climate variability. However, what may put natural systems at greater risk than systems that are actively managed is continued stress from climate change over a long time period. Once a natural system declines, it may take many years to recover. Of particular concern is the possibility that losses to natural systems may be irreversible, such as the loss of species. In managed systems, it is much more likely that there would be intervention to reduce the losses because the economic value at stake is often very high.

Applying the Criteria

Federal agencies are currently making many decisions about the management of natural resources that could be significantly affected by climate change. What the Federal Government decides now about the management of water supplies, forests, wetlands, fish, wildlife, and other issues could limit or foreclose the ability of these resources and their managers to adapt to the future effects of climate change, or could help make us better prepared to deal with an uncertain climate future.

Given the broad criteria of flexibility and robustness, we identified a large class of policy options that could remove inefficiencies, address existing problems, and help insure against the uncertainties posed by climate change to resource systems. Many studies term such options *no regrets* or *low regrets* because they make sense to pursue now, even assuming no climate change. The question that arises is: Why are actions that are supposed to be prudent, anyway, even without the added impetus of climate change, being pursued in such a limited way (5)? Actions that appear reasonable for protecting resources cannot be considered in a vacuum. In reality, there are barriers of many sorts-in information, institutions, and process-even to options that appear to be low regrets. OTA'S policy analysis focused on these barriers and tried to identify ways to overcome them.

Another large class of policy options calls for us to be prepared for the worst. Whether these options will still be seen as no-regrets once climate does change may depend on the rapidity and magnitude of that climate change, and the future response of decisionmakers. If, in the face of significant climate change, the no-regrets options prove inadequate, there could indeed be regrets that substantially more aggressive measures were not taken earlier. OTA has also looked at some of the more aggressive measures that would be appropriate if the likelihood of climate change is considered high.

The policy options presented in this report to enhance the flexibility and robustness of the various resource systems represent a gradation from "learn more about the natural resource system" to "improve the technology or know-how required for adaptation" to "relax the institutional constraints that tend to inhibit the ability or incentive to respond. " This gradation depends on whether the ability to respond to climate change is limited by information, by available technologies, or by the institutions that govern the system.

Coastal systems and water resources (discussed in vol. 1, chs. 4 and 5, respectively) face many institutional factors that may limit adaptation. Theoretically, there is enough water to supply needs throughout the United States, even under climate change. We know how to move water from one place to another and have technologies to save water or even to make fresh water from salt water. However, the complex system of water rights, lack of incentives to conserve water, and limits on the transferability of water result in daunting institutional constraints and inflexibility. In coastal systems, the infrastructure of roads and bridges and subsidized flood insurance encourage a degree of development in high-risk zones that maybe economically unwise even under current climate conditions and sea levels.

In agriculture, market incentives and annual planting cycles make the system quite responsive, or flexible, to change. As long as there are continued efforts in research, technology, and innovation that expand the base on which adaptation can proceed, coping with climate change should be relatively easy for agriculture-barring catastrophic changes (vol. 1, ch. 6). Yet, whether adaptation is optimal may depend greatly on our ability to remove certain institutional incentives that may encourage uneconomic farming of areas where climatic risks are high. In this regard, farm subsidies and disaster-assistance programs need review and, likely, adjustment.

For less-managed systems, our ability to facilitate natural adaptation is limited by inadequate information or understanding of natural processes and by the narrow range of available and suitable technologies for adaptation. In wetlands (vol. 2, ch. 4), sea level rise and changes in the timing and amount of precipitation will exacerbate ongoing habitat loss. Efforts to reduce current loss will make the system more robust and improve chances for adaptation to climate change. Actions to minimize the possibility of irreversible damage should receive high priority. For forests and natural preserves (vol. 2, chs. 5 and 6), climate change may make the continued existence of unique assemblages of plants and animals questionable. Natural areas have become the repository of biodiversity in the United States. Yet little is known about maintaining, changing, restoring, or transplanting natural ecosystems. There is no systematic effort to document what is currently preserved and how that can be augmented or protected under climate change. Enhancing these areas through strategic acquisitions of land or land easements and through innovative coordination of management with adjacent landowners offers great promise as an approach for maximizing protection of biodiversity. Filling in gaps in our knowledge through research would allow us to better manage and protect these areas and to reduce the risk of decline under climate change.

OVERARCHING POLICY THEMES

As we developed and evaluated policy options, using the criteria described above, for the six different resource sectors examined in this report, many sector-specific policy options appeared to coalesce into several broad themes, or problems. Four particular themes were found to be shared by several or all of the sectors:

- geographic and institutional fragmentation,
- inadequate *communication of climate risk,*
- the need for *contingency planning,* and
- an ongoing Federal research effort-the U.S. Global Change Research Progrogram--that will not fill many key *research and information gaps.*

Each chapter addresses these themes within the context of the appropriate resource sector, but the common threads are highlighted here. Below, we describe the overarching themes more fully and illustrate some possible directions Congress could take to begin addressing these broader policy challenges. Box 1-C examines some specific options from the resource chapters, and relates them to these common themes.

■ Fragmentation

A key problem in natural resource management is that the most sensible management units from a resource perspective—watersheds or ecosystems-rarely correspond to the boundaries within which resources are actually managed. Furthermore, resources are usually owned and managed for multiple purposes. Many different government agencies and private owners may have some responsibility for the management of a given resource, with differing incentives motivating its management and use. As a result, resources may be fragmented geographically and jurisdictionally.

One aspect of fragmentation is the geographical division of landscapes and ecosystems that results from uncoordinated development and the encroachment of human activity. Such activity has left few ecosystems intact in the lower 48 States (the Greater Yellowstone Ecosystem is often cited as the most important remaining example). Inmost parts of the country, remaining natural areas have become “islands’ of habitat, surrounded by developed or altered landscapes and vulnerable to a variety of human stresses (see vol. 2, box 5-E). This fragmentation of former large ecosystems has led to greater stress on the natural resources within the remaining fragments. Many natural areas, including the federally pro-

Box I-C-Solutions from General to Specific: Addressing the Overarching Problems

During the course of developing policy options for coping with climate change, OTA heard repeatedly from many experts that climate change alone is not necessarily the most worrisome threat to natural resources. Rather, climate change is likely to exacerbate various trends and problems that already plague natural resource management. Current management policies and practices for coasts, water resources, agriculture, wetlands, natural areas, and forests are perceived in many quarters as being inadequate in ways that not only hinder management today, but could impose greater constraints under a changing climate. Four particular problems were found to be common to several or all of the sectors: 1) institutional and geographical fragmentation; 2) Inadequate communication of information that would improve response to climatic risks; 3) lack of contingency planning and other measures to prepare for extreme events or weather surprises; and 4) information gaps in various key scientific and policy areas.

Addressing these overarching problems will pose numerous challenges for Congress and Federal agencies. All four problems have been recognized to varying degrees in the past, but progress toward solving them has been slow. Attempting to solve any of them could require far-reaching policy changes, but small piecemeal actions could be undertaken for individual resource sectors by many different government agencies or by congressional appropriations, legislation, and oversight committees. Big, bold policy changes could accomplish the job more uniformly or effectively, but reaching agreement on solutions and then garnering sufficient support to implement them could prove impossible. Incremental changes do not require such widespread support and may accomplish specific goals, but such policies can also detract from needed larger changes by leaving the impression that no further action is necessary.

In the resource and research chapters of this report (vols. 1 and 2, chs. 3 through 6), we suggest numerous policy options that address parts of the four overarching problems in ways that are specific to each resource sector. In many cases these resource-specific options could be formulated in broader terms to attempt across-the-board solutions to the overarching problems identified above. Furthermore, many of the sector-specific options are interconnected, and could be more effective if enacted in a coordinated way. In some cases, any of several different resource-specific policy options could forma first step toward solving an overarching problem. A few of these options are described below.

Fragmentation

Options to help reduce institutional fragmentation include:

- Promoting the reestablishment and strengthening of Federal-State river basin commissions to improve coordination among agencies. (Vol. 1, option 5-11—''Water.")
- Promoting integrated resource management at the watershed level, (Vol. 2, option 4-22-''Wetlands.")
- Creating a Federal coordinating council for ecosystem management. (Vol. 2, option 5-12–''Preserves.")
- Amending the Science Policy Act of 1976 (P.L. 94-282) to strengthen the ability of the Office of Science and Technology Policy (OSTP) and the Federal Coordinating Council on Science, Engineering, and Technology (FCCSET) to coordinate research and ecosystem management across agencies. (Vols. 1 and 2, option 3-1-''Research.")

Although these options seem varied, all four address, in some way, the problem of institutional fragmentation and the need for greater coordination and integrated management. If enacted individually, these policies could focus on specific problems in the management of water resources, wetlands, and preserves. However, any of the four could also serve as part of a larger effort to coordinate the management of all three resources. Reinstated river basin commissions could form a local base for watershed management that could be broadened to include attention to wetlands and other natural areas within the watershed. Similarly, a Federal coordinating council for ecosystem management could use watershed units as one level of coordination and examine the interaction of water resources with other natural resources in that unit. The problem in trying to expand any of these individual options to cover the overarching concerns would be in how best to assign authority and enforcement capabilities for any coordinating agency without interfering with the jurisdiction of the agencies to be coordinated.

Options to help reduce geographic fragmentation include:

- Identifying and assigning priorities to the wetlands that are most important to protect and restore. (vol. 2, Option 4-19-- "Wetlands.")
- Directing agencies to modify their criteria for land acquisition to include underrepresented ecosystems and long-term survivability. (Vol. 2, option 5-9-'' Preserve")")
- Using current conservation incentive programs administered by the Secretaries of Agriculture and Interior to enhance the Federal effort to protect natural areas. (Vol. 2, option 5-16-'' Preserve")")
- Protecting highly valued forest sites. (Vol. 2, option 6-4-''Forests.")
- Providing incentives to reduce fragmentation of private forestland. (Vol. 2, option 6-5-''Forests.")

Several of the policy options for wetlands, preserves, and forests either explicitly address the problem of geographic fragmentation or could be used to do so. The options listed above would promote priority setting for land acquisition or restoration of valuable natural areas, including wetlands, forests, and other typesof preserves. Reducing landscape fragmentation could be viewed as a high-priority goal. Furthermore, existing conservation incentive programs of various types could be required to focus on the lands most valuable for preventing or ameliorating fragmentation.

Communication of climate risk

Options to communicate risk through modifying subsidies include:

- Raising premium rates for the National flood Insurance Program (NFIP) policyholders who receive subsidized flood insurance. (Vol. 1, option 4-1-''Coasts.")
- Reducing the Federal share of public disaster assistance. (Vol. 1, option 4-7-'' Coast")")
- Reforming pricing in Federal water projects. (Vol. 1, option 5-5--"Water.")
- Defining disasters formally, with assistance provided only for unusual losses. (Vol. 1, option 6-3--''Agriculture.")
- Improving participation in the crop-insurance program. (Vol. 1, option 6-5--''Agriculture.")
- Eliminating incentives to destroy wetlands. (Vol. 2, option 4-8-"Wetlands.")
- Reducing Federal subsidies, such as Coastal Zone Management funds and flood insurance, in areas that have not established setback or "planned retreat" policies. (Vol. 2, option 4-16-' 'Wetland")")

One of the major ways the Federal Government affects the responsiveness to climate risk is in the distribution of public money for disaster assistance and insurance subsidies. Subsidized and regulated prices distort the perception of changing risks and could slow the response to growing water scarcity and to increases in the frequency of droughts, floods, and storms. The options listed above suggest that policies to reduce or eliminate such subsidies could be beneficial in encouraging greater precautions and faster responses to changing climate risk in nearly every individual resource sector-as well as in reducing Federal spending in an era of constrained budgets. If enacted together, these options could go a long way toward addressing the overarching problem of misperception of risk.

Options to communicate risk through tax signals include:

- Eliminating or reducing tax benefits for coastal development (such as the casualty-loss deduction). (Vol. 1, option 4-16--"Coasts.")
- Reforming tax provisions to promote conservation investments. (Vol. 1, option 5-4--"Water.")
- Using current conservation incentive programs administered by the Secretaries of Agriculture and Interior to enhance the Federal effort to protect natural areas. (Vol. 2, option 5-9--'' Preserves.")

(Continued on next page)

Box I-C-Solutions from General to Specific: Addressing the Overarching Problems--(Continued)

The U.S. Tax Code can provide both incentives and disincentives for financial risks. Tax incentives can be used to encourage behavior that might reduce risks to humans and the environment, including investments in water conservation and in protecting natural areas. Tax disincentives could be used to help prevent unproductive behavior, such as coastal development in high-risk zones or where development leads to the destruction of wetlands or creates barriers against their movement inland as the sea level rises.

Other options to communicate risk include:

- Improving the research and extension process (develop a database on successful practices; expand farmer involvement; provide support for on-farm experimentation). (Vol. 1, option 6-11—''Agriculture.")
- Incorporating climate change scenarios into forest plans and assessments. (Vol. 2, option 6-11—''Forests.")
- Eliminating the even-flow-harvest requirement of the National Forest Management Act (P.L. 94-566), which falsely implies that future timber supplies will be stable). (Vol. 2, option 6-12–''Forests.")
- Incorporating sea level rise into National Flood insurance Program mapping. (Vol. 2, option 4-5--''Coasts.")

The Government is the source of considerable information that can serve to improve private sector response to a changing climate. Outreach and extension services will be valuable in communicating changes in the effectiveness of farm management techniques and crop choices, speeding t he process of adaptation. Inventories, monitoring, climate data, and resource-status assessments will indicate trends in natural resource conditions and signal changes in the future supply of products and service from natural resource systems. Better understanding of these trends will help businesses and individuals to anticipate and adjust more effectively to changing future conditions. Inappropriate signals about climate risk that create an unrealistic expectation of stable conditions may encourage unwise financial investments in resource-dependent communities that are at risk of decline. The public generally is not well-informed about the risks associated with living in coastal areas, and this lack of awareness has led and will continue to lead to large public and private expenditures. Educating people now about the risk of a rising sea level could greatly reduce future damages.

Contingency planning

Options to formalize contingency planning include:

- Creating an interagency drought task force to develop a national drought policy and plan. (Vol. 1, option 5-I&' 'Water.")
- Creating a national flood-assessment board. (Vol. 1, option 5-17--''Water.")
- Establishing criteria for intervention in order to protect or restore forest health through a forest health bill. (Vol. 2, option 6-7—''Forests.")

Droughts, forest fires, floods, and hurricanes have all become the focus of public attention in recent years after events such as the nationwide drought in 1968, the 5-year California drought of 1968-1992, the Mississippi floods in the summer of 1993, and Hurricanes Hugo and Andrew in 1968 and 1992. In many cases, contingency plans set up to deal with such disasters were either inadequate or nonexistent. Policy options for water resources and forests suggest different types of contingency planning that may help address future disasters as the climate changes. Because the presence of forests and wetlands moderates how water moves through the landscape, both should be considered in flood planning and development.

Options that add a measure of "insurance" against catastrophic events include:

- Increasing support for the development of new commercial crops. (Vol. 1, option 6-14--"Agriculture.")
- Conducting research on natural resources to prepare for climate change (restoration ecology, preservation of biodiversity, effective preserve design). (Vol. 2, option 5-2—''Preserves.")
- Directing agencies to modify their criteria for land acquisition to include underrepresented ecosystems and long-term survivability. (Vol. 2, option 5-9—''Preserve")")

- Enhancing forest seed banks and genetics research programs. (Vol. 2, option 6-1—''Forests.")

Preparing for extreme future climate conditions through the development of technologies or institutions will assist in recovery and can help reduce the threat of future damage. The development of crops well-suited to harsher future climate may provide some insurance against a steep decline in our agricultural sector. Contingency preparations for forests and preserves must consider the potential need for active restoration or protection if natural processes become excessively disturbed. Seed banks may provide the material to rebuild a forest in the event of severe decline and loss of species or populations from their natural range.

Information gaps

Options to help decrease these gaps include:

- Supporting long-term research and monitoring on the impacts of climate change on wetlands. (Vol. 2, option 4-24--''Wetlands.")
- Increasing funding for ecological research in the U.S. Global Change Research Program (USGCRP). (Vol. 2, option 5-1--''Preserves.")
- Supporting coordinated research in federally protected natural areas. (Vol. 2, option 5-4--''Preserves.")
- Creating a national program for inventorying and monitoring. (Vol. 2, option 5-5-'' Preserve")")
- Using the Experimental Forests for research on adaptation to climate change. (Vol. 2, option 6-2—''Forests.")
- Using existing monitoring and inventorying efforts to identify causes and effects of forest decline. (Vol. 2,option 6-6--''Forests.")
- Creating an Integrated Assessment program within or outside USGCRP positioned above the agency level, (Vols. 1 and 2, option 3-8-''Research.")
- Creating an adaptation and mitigation research program either within USGCRP or separate but parallel to it. (Vols. 1 and 2, option 3-+'' Research.")

Many policy options suggest particular research questions or promote the use of specific existing programs to address some of the information gaps regarding climate change. Coordinating these different research efforts and ensuring that each considers some of the related concerns of others might yield synergistic results. For example, while the Experimental Forests should be useful sites for examining how forests may adapt to climate change, research could be focused more broadly to consider issues that affect natural areas (including questions of how to maintain biodiversity and how to restore damaged ecosystems) and forested wetlands.

While these research programs in individual areas are forming useful building blocks toward solving the overarching problem of lack of knowledge, a broader program of coordinated research across-the-board could also be attempted. Some of the research listed could be coordinated under the Ecological Systems and Processes priority group in the USGCRP. However, the USGCRP goals and purview need to be broadened to include ecosystem research, adaptation and mitigation research, and an iterative integrated assessment in order to be more useful to policy-making.

tected natural areas, may not be large enough to withstand future stresses such as climate change. Managing smaller areas as individual parcels in an uncoordinated manner and without larger needs in mind has become part of the problem.

A second aspect of fragmentation is the inefficiency that results from a lack of coordination in management across government agencies. It is not uncommon in even relatively small watersheds, for example, for dozens of Federal, State, and local agencies to share jurisdiction overwater and other natural resources. For instance, the Delaware River Basin is divided among four States (fig. 1-3). Responsibility for water resources alone in this basin is divided among at least 10 agencies in each of the four States and among more than 20 Federal agencies. In most basins, responsibility for groundwater manage-

Figure 1-3-The Delaware River Basin

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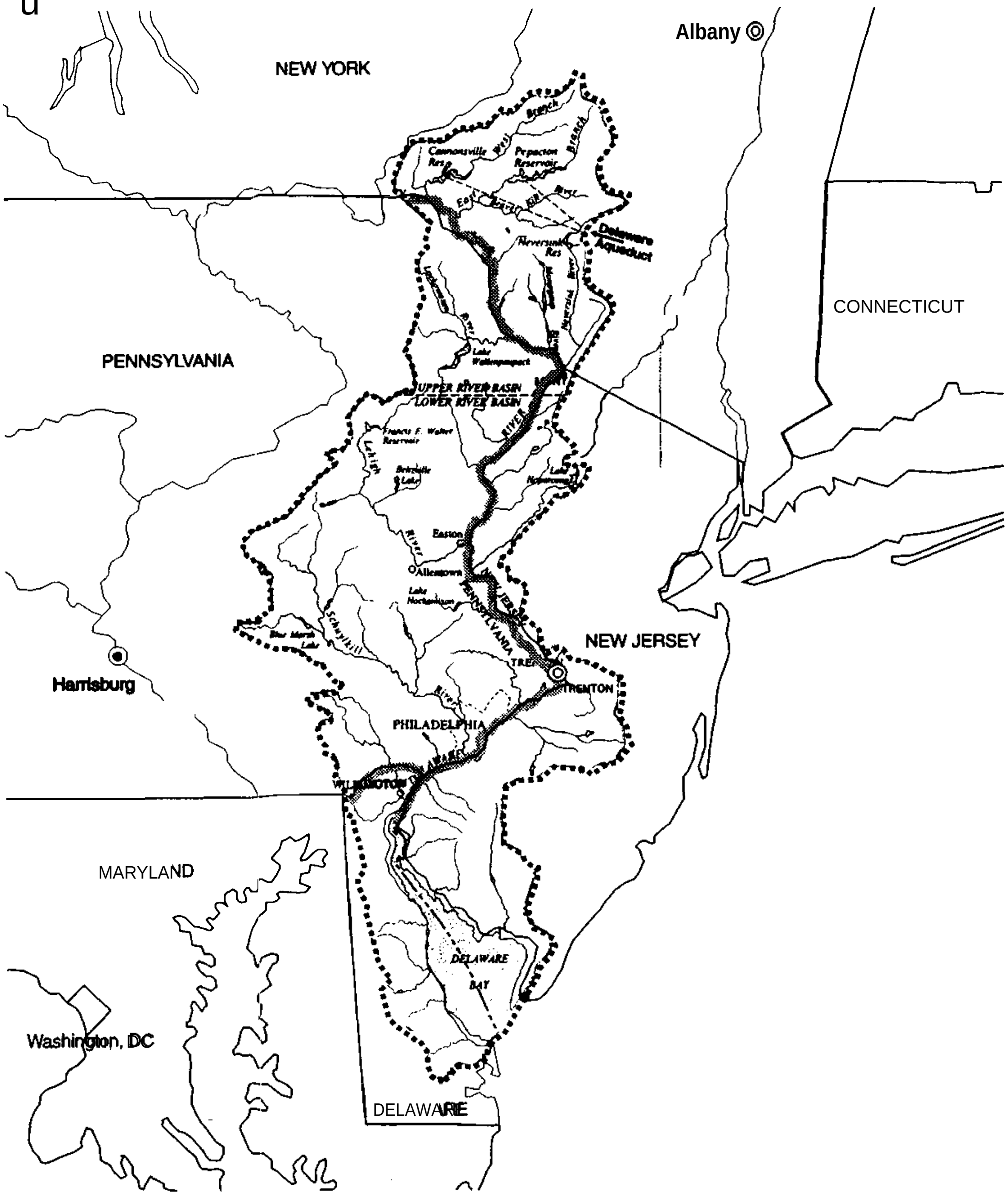

NOTE: As is typical of many watersheds, the boundaries of the Delaware River Basin do not coincide with legislated boundaries. The multiple jurisdictions make management more difficult.

SOURCE: W.E. Harkness, H.F. Uris, and W.M. Alley, "Drought in the Delaware River Basin, 1984-85," in: National Water Summary 1985-Hydrological *Events and Surface Water Resources,* U.S. Geological Survey Water Supply Paper 2300 (Washington, DC: U.S. Government Printing Off be, 1986).

ment is separate from that for surface-water management (see also vol. 1, box 5-D). Water quality and water quantity are usually treated separately. And jurisdiction over navigation, recreation, flood control, and wetlands may also be split, although all these aspects of water resource management are related and may affect one another. Problems are encountered in managing a single reservoir as if its operation does not affect how others within a basin are operated, or in managing to control floods without considering the role of wetlands. The result of this jurisdictional fragmentation is often seen in conflicting efforts, high management costs, and foregone opportunities to provide better overall service. These inefficiencies may be of increasing concern if climate changes threaten the supply and services of natural resources. Box 1-D describes the complexities of trying to manage a growing urban center, agricultural areas, and the Everglades of South Florida (see also vol. 1, box 5-B).

More effective management for coping with current and potential future stresses on natural resources and built systems is possible and needed. Today's agency-by-agency, owner-by-owner, and system-by-system management approach leaves much to be desired. Many improvements can be made by going beyond our customary fragmented style of management to consider more comprehensively the services of watersheds, ecosystems, and landscapes (see vol. 2, box 5-F). Within most sectors or systems examined in this report, we have identified options that can begin moving toward more integrated management and reduced geographical fragmentation: breaking down institutional barriers among agencies, acquiring and consolidating natural areas, and providing private owners with incentives to maintain the environmental services of a landscape. Regional priorities could be used to direct activities in regulatory, acquisition, and incentive programs. We also consider some more fundamental changes, such as creating major new programs and reorganizing agency responsibilities, which can be pursued if the political will exists. However, neither breaking down institutional barriers nor altering private incentives will be easy. Watershed management, for example, has been discussed for many years, but established styles of management have changed little to date. Nevertheless, watershed management seems to be a concept whose time has come: the Environmental Protection Agency (EPA), backed by the current Administration, has strongly advocated the approach, and watershed management is being considered in current legislation to reauthorize the Clean Water Act (P.L. 92-500) (see vol. 1, box 5-c).

More integrated planning and management along watershed and ecosystem lines is likely to be one of the best ways for the Nation to promote the flexibility, robustness, and efficiency that is desirable in coping with the uncertain impacts of climate change.

Communication of Climate Risk

If climate changes as predicted, resource managers and individuals will find it necessary to adjust to new circumstances. Certain parts of the country are likely to become much less desirable

NOAA

Hurricanes and other tropical storms cause millions of dollars' worth of damage each year as homes, boats, and businesses are destroyed by high winds and water. Some Federal programs and regulations encourage redevelopment in high-risk areas without requiring appropriate safety measures.

places to live and work. Even where climate changes are less harsh, current management practices and lifestyles may not continue to be appropriate. The speed with which resource managers and individuals can recognize and respond effectively to new climate conditions will largely determine the economic and social costs of climate change. Adaptation to change is likely to be delayed by the inherent difficulties in recognizing climate change against the background of normal climate variability. Responsiveness to changing climate risks maybe further impeded by existing Federal programs designed to protect individuals from the financial risks of climatic extremes. It maybe enhanced by providing information about the nature of climate change risks, the changing resource situation, and the likely success of particular adjustments in resource-management techniques. Effective communication of the nature of climate-related risks can be promoted through formal educational efforts or through appropriate incentives.

The Government could better communicate climate risk by reducing the various public subsidies for developments in areas of high risk. The public has come to depend heavily on government disaster assistance and subsidized insurance programs, which helps reduce exposure to the financial risks from climate extremes. Such programs have been valuable in allowing the productive use of resources in areas of highly variable climate. Problems may arise, however, if the financial buffer provided by these Federal programs unintentionally encourages people to move into environments where they may be exposed to greater risk in the future, or reduces incentives to take adequate precautions against climate risk. Because development decisions are not easily reversible, and the consequences of decisions taken now are, in some cases, likely to be with us for many decades, it seems prudent to begin reexaminingg policies that may encourage development in climate-sensitive areas. Private citizens should recognize the true costs of extending farms into economically marginal areas, building structures in areas of high forest-fire risk, or locating buildings in coastal erosion zones.

We assessed two systems in which a reexamination of current risk protection policies may be especially important in the face of climate change: coastal areas and agriculture (see vol. 1, chs. 4 and 6). Flooding and erosion are of particular concern in coastal areas, and these hazards could increase in a warmer climate. We discuss options in the coastal and agriculture chapters that could help owners respond more effectively to climate change and that would decrease potential future exposure to climate risk. For example, the National Flood Insurance Program has been only partially successful in reducing the need for taxpayer-funded disaster assistance and in encouraging local mitigation efforts. In agriculture, Federal Crop Insurance, various disaster-assistance programs, and irrigation subsidies all tend to distort the manner in which farmers respond to climate risks. (See box 1-Eon water allocation in the Sacramento-San Joaquin River System and box 1-F on agriculture in the prairie-pothole region.) Improvements can and should be made in these program to ensure that in the future, individuals, communities, and the Federal Government are not exposed to excessive costs.

Equally important may be quickly communicating the detection of any change in key climate variables and other information that will assist in the responses to changing climates. Farmers and foresters, for example, may be reluctant to alter practices until they are convinced climate has actually changed. The potential role of the Extension Services in tracking the changing success of farming and forestry practices and spreading this information to managers may prove important in reducing the costs of adaptation.

Contingency Planning

The goal of contingency plarnning is to minimize losses from natural disasters or accidents by preparing in advance to take appropriate actions.

Contingency plarming is important where the threat of significant losses is high in the absence of preparation and prompt response--as is the case with floods, forest fires, droughts, and hurricanes (see vol. 1, chs. 4 and 5 and box 4-C; vol. 2, box 5-I). Climate change could affect the intensity or number of extreme climate events, making preparedness perhaps even more important than it is now. However, adequate contingency plans do not exist for all parts of the country that are vulnerable to extreme events. For example, only 23 States have drought-management plans (197). The States that do have them, however, have generally adapted better to droughts than those without plans (197). We identified options that could help mitigate damages, including the ecological harm caused by natural disasters. Improvements in contingency planning would be helpful both to minimize near-term damages and to prepare for potentially greater damages caused by climate change.

States have a key role in planning for most extreme events and must continue to do so. States should be encouraged to develop contingency plans or to refine them with climate change in mind. The Federal Government also has a role in planning for natural disasters, with many agencies involved in some way in this activity (see cartoon on page 34). However, the Federal Government could do better at defining the respective roles of the agencies that have responsibilities for extreme events. It could also promote stronger coordination among Federal agencies and among the various levels of government in establishing requirements for assistance and in providing such assistance in a more timely, consistent, and equitable manner.

Contingency planning is also important when emergency measures are likely to be controversial; it allows potential responses to be considered in advance when there can be rational debate. Such controversies are very likely to be associated with any efforts to restore the health of natural ecosystems that have been severely harmed by climate-related stresses. This is well-illustrated by difficulties now faced in responding to "massively destructive forest health problems" in the Blue Mountain forests of Eastern Oregon (176; see vol. 2, ch. 6 and box 6-E). Although there is general agreement that major changes in management are needed in those forests, the response has been slow, and agreement about how to proceed has been hard to achieve. Procedures for responding to ecosystem health emergencies should be established.

Research and Information Gaps

The individual resource chapters outline the important research gaps that need to be addressed for coasts, water resources, agriculture, wetlands, preserves, and forests. Overall, we found that various strategies for coping with climate change can be identified for managed natural-resource-based systems (including the coastal zone, water resources, and agriculture-see vol. 1, chs. 4-6). Some of these strategies may require continued support for research on new technologies or management practices that will enhance the potential for adaptation. For natural systems, however (e.g., wetlands, unmanaged forests, and nature preserves-see vol. 2, chs. 4-6), the informational gaps in our understanding of these systems are so large that realistic response strategies are difficult or impossible to identify now (see also vol. 2, box 5-K).

Although an estimated $900 million is spent annually on what can be considered research in "environmental life sciences" (54) or "environmental biology,"[6] there is currently very little research directed specifically at protecting natural areas under climate change and helping land managers modify management strategies to re-

6 J. Gosz, Executive *Secretary,* Subcommittee on Environmental Biology, Committee on Life Sciences and Health, Federal Coordinating Council for Science, Engineering, and Technology, personal communication, Sept. 14, 1993, Only 11 percent of these expenditures overlaps with the Federal Global Change Research Program budget.

Box I-D–Climate Change, South Florida, and the Everglades

Lying dose to sea level and in the preferred path of a sizable percentage of Atlantic hurricanes, South Florida is potentially one of the most vulnerable areas of the United States to climate change. It is also one of the most distinctive. South Florida's famed Everglades, a vast subtropical wetland of which about one-seventh is preserved in Everglades National Park, is seen by many as one of the crown jewels of the U.S. National Park System. Miami, Palm Beach, and other coastal communities in South Florida makeup one of the most popular seaside vacation destinations in the world. Despite hurricane and flood hazards, these cities have experienced phenomenal growth in recent years. In addition, varieties of crops can be grown in the warm, subtropical climate that grow nowhere else in the United States. And Miami has become a gateway between North and South America, transforming South Florida into an important international crossroads.

Despite, or perhaps because of, its distinctiveness and popularity, South Florida is under stress and, like a few other heavily developed parts of the United States, beginning to bump up against limits to growth. The critical factor is water. Although the region receives an annual average of 60 inches (152 centimeters) of rain, annual evaporation can sometimes exceed this amount, and rainfall variability y from year to year is quite high, resulting in periodic droughts and floods. In the past century, moreover, South Florida has been transformed from a virtual wilderness into a complex, interconnected system of developed and undeveloped land. The main elements of this system-the growing urban sector, agricultural areas, and the Everglades and other remaining natural areas-must all compete for the limited supply of water, and the competition is increasing with every new resident.

Much of the growth of South Florida has occurred since 1870. Then, fewer than 100 people lived in what are now Dade, Broward, and Palm Beach Counties. Now, about 5.2 million people occupy the same area. The vast unaltered Everglades, which originally extended from Lake Okeechobee to Florida Bay, were seen by early settlers as hostile to human welfare and completely without value. Encouraged by a grant from the U.S. Congress, the State of Florida began draining these "useless" wetlands for agriculture, and by the early 20th century, the natural character of the Everglades had begun to change. Farmers planted sugar cane and a variety of vegetables in the drained area south of Lake Okeechobee now known as the Everglades Agricultural Area (EAA).

The initial drainage system worked well enough during normal years but was stressed during occasional abnormal events and failed completely during a major hurricane in 1928. At that time, 2,000 people died in the EAA when the protective dike around Lake Okeechobee burst. This incident prompted the initiation of a massive public works project, as attention shifted from drainage of wetlands to flood control. Eventually, an 85-mile (137-kilometer)[1] earthen dike was built around Lake Okeechobee, and the meandering 98-mile Kissimmee River, which fed the lake from the north, was transformed into a canal 48 miles long and 33 feet (10 meters) deep. Flooding problems diminished, but the former broad, riverlike system north of Everglades National Park has been greatly altered into a series of canals and pools. The former sheet-like flow of water to the park, necessary to its health, has been blocked. Today, the area has more than 1,395 miles of canals and levees and 143 water-control structures.

Projects to expand the supply of water to growing urban centers proceeded in tandem with flood-control projects. To accommodate demands for agricultural and urban expansion, diking and draining of wetlands continued, and as the expansion progressed, more water was diverted for these purposes. Today, additional water is diverted for sewage dilution, pest control, and frost protection. Some water is used to recharge aquifers that supply cities east of the Everglades and the populated areas of the Florida Keys. Large quantities of water that could be recycled or used to recharge urban aquifers are dumped into the Atlantic Ocean (see vol. 1, ch. 5, and vol. 2, ch. 4, for complete discussions of water and wetland issues).

A major effect of this decades-long restructuring of the natural hydrological system has been to drastically reduce the supply of water from the Kissimmee River watershed that reaches the much-diminished-in-size

1 To convert miles to kilometers, multiply by 1.609.

Everglades. The natural system has suffered in several ways as a result: 1) the abundance of species characteristic of Everglades habitats (e.g., wood storks, white ibis, tri-colored herons, and snowy egrets) has declined dramatically in the past 50 years, 2) more than a dozen native species have been listed as endangered or threatened (e.g., the Florida panther, snail kite, Cape Sable seaside sparrow, American alligator, and American crocodile), 3) nonnative and nuisance species have invaded the area (e.g., Melaleuca quinquinervia and the Brazilian pepper tree), 4) sizable land subsidence and water-level declines have occurred throughout the region, 5) water quality has been degraded by agricultural runoff containing excessive nutrients, such as phosphorus, 6) saltwater intrusion of coastal aquifers has occurred, 7) vulnerability to fire has increased, and 8) massive algal blooms have appeared in Florida Bay, accompanied by die-offs of shrimp, lobster, sponge beds, and many fish.

The impacts of development have not been limited to natural areas. As water use in the region has grown, susceptibility to periodic droughts has increased. A 1981 drought, for example, led to mandatory water restrictions for half the counties of South Florida and water rationing in the EAA. Pollution from cities, as well as from agricultural areas, has added to water-quality problems. Saltwater intrusion threatens aquifers used for urban water supplies.

Everglades National Park was created in 1947, the culmination of efforts that began in the 1920s. The transition of the Everglades from being perceived as "worthless land" to an important preserve worthy of designation as an International Biosphere Reserve and World Heritage Site took decades, but preservation of this area and restoration of other degraded wetlands are now considered high priority by a broad spectrum of people and organizations. Although there is broad agreement that the hydrology of the Everglades should be restored to a pattern similar to that found in the original system, it will not be easy to balance the needs of the Everglades for water with the similar needs of other users.

South Florida's Everglades and coastal areas, dearly already under stress, face an unusually difficult problem in the light of global climate change. Both are already vulnerable to sea level rise and intense tropical storms (see vol. 1, ch. 4). (Damage from Hurricane Andrew, for example, was not confined to urban areas-coastal mangrove forests were heavily damaged, as were trees in many densely forested hammocks.) Climate change could increase the current vulnerability to these events. Climate change may also result in a hotter and drier climate for South Florida, although predictions from general circulation models (GCMs) are not consistent on this point. Whatever occurs, the future is likely to be increasingly stressful for South Florida. Cities are likely to continue to grow and will almost certainly be protected from sea level rise, but the expense of protecting them could be immense. The Everglades, once deemed worthless, is now considered a valuable natural resource. As valuable as it is, however, the Everglades will probably not receive the same attention as cities threatened by rising seas will. Farmers are likely to resist attempts to hinder or reduce long-established patterns of agriculture in favor of other uses for water. In short, South Florida is a system increasingly "close to the edge." The flexibility to satisfy competing interests for water and land has been reduced by actions taken since the turn of the century, and climate change may further reduce flexibility.

In recent years, some efforts have been made to offset some of the damage to the Everglades and restore some of the lost flexibility to the natural system. In 1970, for example, Congress directed that not less than 315,000 acre-feet (389 million cubic meters) of water be delivered annually to Everglades National Park. In 1989, Congress enacted the Everglades National Park Protection and Expansion Act (P.L. 101-229), one purpose of which was to enable more natural flow of water through a portion of the park. More recently, the Federal Government sued the Florida Department of Environmental Regulation for not upholding its own water-quality laws, thereby allowing degradation of the Everglades to continue. As a result, the State has agreed to design and construct treatment areas in the EAA where drainage could be filtered before it is discharged to the park. The State has also directed the South Florida Water Management District to implement an Everglades Surface Water Improvement and Management Plan. Finally, as authorized in the 1992 Water Resources Development Act (P.L. 101-640), the U.S. Army Corps of Engineers will soon begin a long-term project to restore the Kissimmee River to an approximation

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Box 1-D—Climate Change, South Florida, and the Everglades—(Continued)

of its original meandering route, thereby increasing wetlands north of Lake Okeechobee, helping to improve water quality in the lake, and increasing the water-storage capacity of the entire Everglades system.

Although important steps are being taken to restore the Everglades, some major obstacles are stymieing the more comprehensive ecosystem planning that will be required to address the full range of South Florida's current and climate-change-related problems. One of the most vexing, and one encountered many times in OTA's study, is the lack of coordination among the responsible State and Federal agencies. Part of the problem is a result of a lack of shared values among agencies and among the constituencies they represent. Furthermore, each agency has a different mandate, and agencies' jurisdictional boundaries seldom coincide with boundaries of natural systems. One might expect that the preservation mandate of the U.S. Fish and Wildlife Service and the Florida Department of Environmental Regulation would often clash with the flood-control mandate of the Corps of Engineers and with the interests of EAA farmers, and such has been the case in South Florida. However, lack of coordination has extended even to agencies with similar mandates; a prominent example has been the difficulty of reconciling the National Park Service's ecosystem-wide approach to restoring the Everglades with the Fish and Wildlife Service's mandate under the Endangered Species Act (P.L. 100-707) to focus on protection of individual species.

Recently, Interior Secretary Bruce Babbitt expressed a strong interest in Everglades National Park and has made clear his intention to get the National Park Service and the Fish and Wildlife Service to work more closely together to develop a common policy. Babbitt has also announced plans to form a Federal task force in an attempt to overcome some of the coordination problems.

The broader challenge for the region is to manage this complex system in an integrated fashion to maximize the health of all its diverse elements. This is no small challenge because it may be very difficult to sustain agriculture without environmental costs, for example, or for urban areas to continue to grow indefinitely without some restraints. The effort to sort through these problems must take place with some understanding of what climate change may mean.

SOURCES: S. Light, L. Gunderson, and C. Holling, "The Everglades: Evolution of Management in a Turbulent Ecosystem," University of Florida, Arthur C. Marshall Laboratory, unpublished manuscript, 1993; National Audubon Society, *Report of the Advisory Panel on the Everglades and Endangered Species* (New York: National Audubon Society, 1992); J. de Golia, *Everglades: The Story Behind the Scenery* (Las Vegas, NV: KC Publications, Inc., 1978); K. Kemezis, "Babbitt To Test Ecosystem Policy in the Everglades," *Environment Week*, Feb. 25, 1993.

spend to climate change. In 1992, only $8 million was spent on research focused on adaptation to climate change.[7]

The U.S. Global Change Research Program (USGCRP) is a $1.4 billion research program. However, as currently designed, it will not provide either the practical technologies that might make us more prepared for climate change or the ecological information that would be helpful in providing policy guidance and adaptation options for natural systems. Overall, USGCRP is more focused on understanding the causes for and rates of climate change[8] than on examining the ecological and human impacts of change (see ch. 3 for a more complete explanation of USGCRP). The agencies primarily responsible

[7] 'I&Working Group on Mitigation and Adaptation Research Strategies (disbanded in 1992) of the Committee on Earth and Environmental Sciences of FCCSET identified Federal research that focuses on or contributes to adaptation to global change (24).

[8] USGCRP is designed to produce a predictive understanding of the Earth system and focuses on three interrelated streams of activity: documenting global change (observations), enhancing understanding of key processes (process march), and predicting global and regional environmental change (integrated modeling and prediction). For FY 1994, a fourth activity stream, assessment, was added.

Box l-E—Water Allocation and the Sacramento-San Joaquin River System

The complexity and divisiveness of western water problems-and the potential for climate change to exacerbate those probleme--is well-illustrated in the continuing battle over allocation of water in California. The Sacramento-San Joaquin River System, and especially the Delta area where the two rivers come together in Northern California, is the focal point of this conflict. Before western water development began, about 40 percent of California's runoff converged into the Sacramento-San Joaquin Delta on its way to San Francisco Bay and, eventually, the Pacific Ocean. However, about half of this water is now diverted to Southern California, the San Joaquin Valley, and parts of the Bay Area the the massive State Water Project (SWP) and central Valley Project (CVP). The water delivered through these huge "plumbing" systems has enabled California's semiarid Central Valley to become one of the Nation's prime agricultural areas and has been partly responsible for the phenomenal population growth of Southern California's mild coastal areas.

Agriculture is now firmly established in the Central Valley, and about 16 million people--over 70 percent of the State's population-now live in Southern California. Water supply is crucial to California: it has been the basis for most agricultural, industrial, and economic development. However, the transfer of water from Northern to Southern California has not come without a cost to the river system and the State. Water supply and allocation issues directly conflict with water-quality and ecosystem concerns, and they pit interests of Southern Californians against those of Northern Californians. Three issues are of special concern.

Delta fisheries-The Delta and extended Sacramento-San Joaquin River System provide important habitat for over 40 species of fish. Coho and chinook salmon, steelhead trout, and striped bass all reside in the river system atone point in their lives and have been especially important to the recreational and commercial fishing industries. Yet these species of fish have declined 50 percent or more since the early 1960s. Fewer than 500 winter run salmon have returned to spawn each year in the Upper Sacramento in recent years, compared with the 60,000 per year that returned 20 years ago. Only 432 steelhead returned in 1966 compared with over 17,000 in 1967 (16). The Delta smelt is dose to extinction. Causes of these dramatic declines include loss of habitat; water pollution; dam, levee, and diversion-facility obstructions; and drought. When conditions are poor in the Delta-when flows are low and water temperatures and exports are high-losses of young, ocean-bound salmon can be very high.

Fishermen, as well as fish, have suffered. Fish losses have cost the local economy over $15 million per year in recent years. In effect, the benefits to people who receive water diverted from the Delta have come partially at the expense of both fish and fishing interests. in March 1993, the U.S. Fish and Wildlife Service and the National Marine Fisheries Service invoked the Endangered Species Act (P.L. 100-707) to protect winter run chinook salmon and Delta smelt, setting limits on t he operations of the Central Valley Project and intensifying a dispute between State and Federal officials on how best to protect the Delta.

Delta farmland and levees--The Delta, once a natural marshland, was developed for farming around the turn of the century and now contains almost 550,000 acres (223,000 hectares)[1] of rich farmland. The marshland was converted to a mosaic of over 70 islands by building over 1,100 miles (1 ,600 Kilometers)[2] of levees. The levee system is fragile, however. The peat soils of the Delta have been gradually compacting, requiring that levees constantly be raised or repaired. Many of the levee-surrounded Delta islands are now wel below sea Ievel. Maintenance of the levee system is important for protecting life, property, and infrastructure from flooding on Delta islands. Permanently flooded islands would also have major adverse effects on both water quality in the Delta and freshwater supplies. Since 1960,24 levees have failed, and with each year, the fate of these islands becomes more uncertain.

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1 To convert acres to hectares, multiply by 0.405.

2 To convert miles to kilometers, multiply by 1.609.

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Box I-E–Water Allocation and the Sacramento-San Joaquin River System--(Continued)

Water quality-Water quality in the Delta is of concern because of possible salinity intrusion into the western Delta from San Francisco Bay, wastewater discharges that contain chemical pollutants, and the inflow of agricultural drainage water that may contain pesticide residues and other toxic agents (18). Maintaining water quality and ecological health in the Delta (by, among other things, ensuring that an adequate amount of fresh water reaches the Delta) is legally required by the State but may conflict with water transfers and local consumptive uses. This is especially true during drought, when there may not be enough water to fulfill all demands. Drought poses another problem as well: during low-flow periods, water temperature in system rivers increases, and this has contributed significantly to the decline of cold-water anadromous fish spades in recent years.

In sum, Californians are making heavy demands on the Sacramento-San Joaquin River System. They recognize that the means of transferring water from the Delta must be improved to maintain water quality and to enable more efficient transfer of supplies to the southern part of the State, but the issue has proved to be one of the most controversial water problems in the West. In 1982, for example, California voters defeated a referendum to build the so-called Peripheral Canal around the Delta to improve the system'sufficiency. Northern Californians overwhelmingly rejected the proposal, for fear that the Delta's environment would not be adequately protected and because they perceived that populous Southern California was attempting yet another "water grab." Although there was more support in Southern California, many in that part of the State feared the project's high cost.

Studies of the potential impact of climate change in California suggest-but have by no means proven-that the regional effects of climate change could be reduced mountain snowpack, a shift in runoff patterns (i.e., in timing, amount, or duration of precipitation), and large decreases in summer soil moisture. Specifically, a possible result of warming temperatures is that more winter precipitation will fall as rain and a reduced mountain snowpack will start melting earlier in the spring. As a result, reservoirs would fill faster. Because a portion of reservoir space must be reserved for flood-control purposes, the additional water would have to be spilled. Although California's total water budget might remain the same, less would be available during the summer, when water demand is highest. The reduced snowpack in effect represents the loss of one or more storage reservoirs. Maintaining adequate freshwater flow to San Francisco Bay would be more difficult in summer and could increasingly conflict with water needed for consumptive purposes. Summer temperatures would also likely increase in the Sacramento and other rivers and represent a threat to fish.

A further complication could be sea level rise. The Intergovernmental Panel on Climate Change predicts a total sea level rise of 26 inches (65 centimeters)[3] by 2100. Such a rise would inundate the entire Delta area and have devastating effects on Delta islands and water quality. A sea level rise of more than 2 feet would transform the current 100-year high-tide peak at Antioch, a western Delta location, into a 1 in 10 event-making such rare occurrences more common. Levees would be even more expensive, or even impossible, to maintain. Because the Delta islands are developed for farming and valued for helping preserve water quality, the initial response to incremental sea level rise is likely be to try to preserve the islands. In the long run, a phased retreat from the Delta may have to be considered (142), Choosing between preservation at any price and abandonment would not be easy.

if the above impacts occur (or worse, if California's water budget actually decreases), maintaining California's water supplies for consumptive purposes and maintaining the health of the Delta will be a great challenge. This would be especially true during droughts, which, if more common than--and as extreme as-the current drought in California, could have devastating impacts. A suite of demand-and-supply management and supply-augmentation responses to the State's water problems is being considered. No one response will be sufficient. Conservation and water marketing could significantly ease California's water problems, but building new reservoirs and even some desalination plants and other responses may be needed as well.

3 To convert inches to centimeters, multiply by 2.540.

SOURCE: Office of Technology Assessment, 1993.

Box I-F-Changes in Agriculture and the Fate of Prairie Potholes: The Impacts of Drought and Climate Change

The prairies comprise millionsof acres over a vast geographical area that includes parts of Canada, and the states of Montana, North Dakota, South Dakota Minnesota, and lowa.The region is characterized by a glaciated, depressed topography with poorly defined drainage that results In numerous small lakes and wetlands known as prairie potholes.[1] Millions of potholes dot the landscape, providing an impermanent water source for the region's agricultural operations and diverse wildlife, including migratory waterfowl. Since the early 1960s, a general shift in the structure of the agricultural economy has occurred in the prairie region, involving a move toward more-intensive farming practices (80). The drainage of prairie potholes has been accelerated in order to bring more land into production and to increase yields on existing cropland. However, drought conditions in recent years have evoked concerns about the sustainability of the regional agriculture and wildlife and have raised questions about impacts that may result from climate change.

The drying effects of climate change are certain to affect the prairie-pothde region by altering aquatic conditions. Agricultural operations and wildlife rely on prairie potholes for water. An increase In temperature, which would influence aridity in continental interior areas, would reduce available volumes, thereby putting both farming and waterfowl at risk. In addition to changes in the availability of surface water, water storage in the soil is likely to decrease (134). Temperature changes may also mean an extended growing season, which could alter the nesting and feeding habits of wildlife. In total, climate change will affect the region by increasing existing stress on the prairie-pothole ecosystems and agriculture.

Agriculture operations in the prairie region have long provided the bulk of the Nation's wheat supply. Wheat is well-suited to the region's dryland agriculture, with the majority of precipitation falling during the growing season and with relatively cod temperatures keeping evapotranspiration rates down. Farming in the region has become more and more intensive as agriculture has become increasingly mechanized. These developments have had a considerable effect on the fate of prairie potholes, which have decreased from 20 million to 7 million acres (8 to 3 million hectares)[2] leaving only 35 percent of the original pothole acreage intact (179). A poor farm economy in the 1980s coupled with mechanization caused prairie farmers to push every possible acre into production. North Dakota's potholes were being drained at an estimated rate of 20,000 acres per year to support conversion to agriculture (179). And drainage rates became similarly high in other prairie States, as farmers recognized the potential value of new farmland.

Now, although 20 percent of all remaining prairie potholes are protected? prairie potholes are among the most threatened ecosystems in the United States. They provide prime nesting grounds and habitat for a multitude of waterfowl and other wildlife. Since the 1970s, populations of three common duck species (the mallard, the pintail, and the blue-winged teal) have declined dramatically. Populations of some other spades of duck less dependent on potholes in agricultural regions have increased. The mallard, pintail, and blue-winged teal nest in the drought-prone zone of intensive agriculture (1 19). These migratory waterfowl have lost not only extensive areas of breeding habitat, but also adjacent vegetated areas once used for food and cover. Here, the detrimental effects of the loss of wetlands cleared for agricultural use are dramatic; wildlife populations have likely been cut in half (80).

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1 Prairie-pothole ***wetlands are*** relatively shallow, water-holding depressions that vary in size, water permanence, and water chemistry. They are located in the glaciated portion of the North American Great Plains and are the single most important breeding area for waterfowl on this continent (63). They also support a variety of other Wildlife.

2 To convert acres to hectares, multiply by 0.405.

3 Protection includes, but IS not limited to: ownership by Federal or State governments, short-and long-term government easements, and ownership by private conservation groups.

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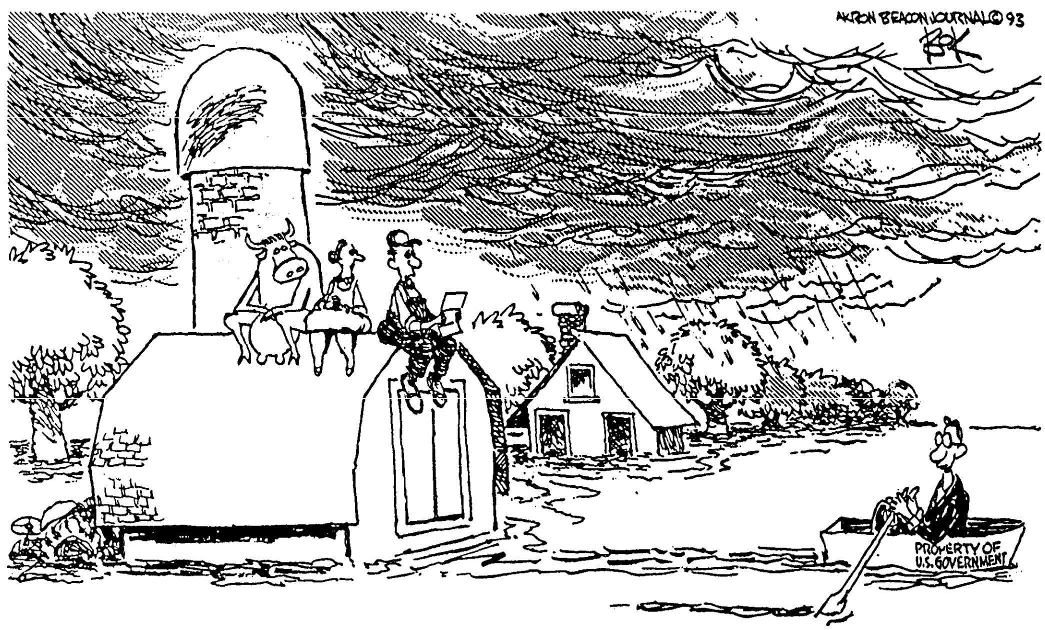
Box I-F-Changes in Agriculture and the Fate of Prairie Potholes: The Impacts of Drought and Climate Change-(Continued)

Though these changes have been occurring over along period of time, effects were most dramatic during recent drought conditions in the region. Severe drought marked both the 1988 and the 1989 growing seasons in North Dakota the heart of the country's spring wheat production area (143). This dry spell was the second to occur during the 1980s and the fourth serious drought in the past three decades (143). The lack of precipitation and subsequent loss of soil moisture resulted in dramatic decreases in agricultural yields and in abandonment of some cropland. Despite the grain crop losses (some more than 70 percent), net farm income and farmed acreage did not suffer. This was basically due to government drought assistance, in the form of insurance and direct aid. The combination of insurance, aid, and the higher grain prices resulting from the drought helped farmers avoid losses that might ultimately have led to extensive farm failure and abandonment.

Climate change may significantly alter growing conditions in the prairie region. Changes resulting from global warming may decrease both water depth and the number of ponds holding water in t he spring and summer. This aspect is likely to further influence the degradation of waterfowl and wildlife habitat and to upset populations. Waterfowl may respond by migrating to other areas, relying heavily on the semipermanent prairie-pothole wetlands, remaining on permanent wetlands but not breeding, or failing to renest as they currently do during drought (160). On the other hand, drier conditions in these shallow, temporary, seasonal wetlands will make land-use conversion to agriculture much more reasonable in terms of expense and ease. Long-term changes in agricultural activity in the region, caused by economics and climate change, are sure to affect the fate of prairie potholes and the waterfowl and wildlife they support, placing them at further risk.

SOURCE: Office of Technology Assessment, 1993.



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"LOOKS LIKE A DISASTER RELIEF CHECK, CROP LOSS COMPENSATION, AND A FINE FOR DISTURBING A WETLAND' for research and management of public lands (the Department of the Interior (DOI), the U.S. Department of Agriculture, the National Science Foundation and EPA) combined receive less than 30 percent of the total funding for Ecological Systems and Dynamics (less than 5 percent of the total USGCRP budget). Given that such research on ecological and human impacts may take years or decades to produce results, the slow process may cost us the ability to respond to global change in areas that are especially at risk to irreversible damage. In addition to understanding climate impacts and effects, it is important to know how to minimize socioeconomic impacts. Ultimately, to be useful in planning for an uncertain climate, USGCRP must include ecosystem research that can feed into management, socioeconomic analysis, and adaptation research. An assessment process that incorporates all these categories and permits inputs from stakeholders and policy makers is necessary to make USGCRP truly policy relevant. This is a much broader definition of "assessment" than USGCRP can accommodate given its current research program and structure.

NEAR-TERM CONGRESSIONAL ACTION

In the resource chapters (vol. 1, chs. 4-6, and vol. 2, chs. 4-6) of this report, a series of "first steps' ' is outlined to illustrate ways to begin incorporating climate change considerations into statutes, policies, and programs relating to various natural resource--coasts, water, agriculture, wetlands, preserved lands, and forests. The first steps for the resource chapters are summarized briefly in the last section of this chapter. Several of the first steps focus on actions that offer important and immediate benefits, even without climate change as an additional factor justifying them. Several targets of opportunity in the near-term congressional agenda, in the announced and potential initiatives of the new Administration, and in the programs of the various agencies can be capitalized upon now.

Likewise, the USGRP offers annual opportunities for changes. Chapter 3 discusses several directions the program could take; many of these options are included below as possible near-term congressional actions. The process of policy development in government is not so orderly that one can lay out and follow a detailed plan of logical first steps, followed by logical second steps, and so on. Regular congressional reauthorization cycles for major natural resource programs, the annual budget cycle, election cycles, the fragmentation of responsibilities among congressional committees, and still other policy-making realities provide the context in which decisions about climate change will be made. Seen in this light, the choice of frost steps is significantly influenced by an assessment of where the opportunities lie.

Annual Appropriations

Even if Congress did nothing else, each year it would enact legislation appropriating money for carrying out governmental programs. Thus, an immediate and recurrent annual opportunity to address many of the issues considered in this report is through the appropriation process. Most simply and directly, to narrow the breadth of uncertainties that exist today, Congress can ensure adequate levels of funding for existing climate-change-related research programs. Through the appropriation process, Congress can also encourage natural resource management agencies to carry out their monitoring and research programs in ways that meet their intended objectives while simultaneously producing data that could be useful to their own or other agencies' climate change research efforts.

The annual appropriation process is also the means by which Congress makes major long-term investments-for example, in land acquired for National Parks and wildlife refuges and in dams and other water resource projects. Until now, climate change considerations have not been a factor in deciding whether any of these investments were prudent. One could justify inclusion of such considerations now because climate change has the potential to lessen the value of such investments. Thus, Congress could require that the land-acquisition, water-resource-development, and other similar proposals brought before it be accompanied by explicit evaluations of how climate change may affect the long-term viability of the investment. Alternatively, in the case of lands proposed to be acquired for conservation purposes, Congress could direct that the criteria by which agencies rank their acquisition priorities include some consideration of potential climate change impacts on those lands or their resources. Building up the Nation's reserve of protected land would help stem some climate change impacts by reducing fragmentation and, possibly, reducing other threats to natural area resources. Increased protection and reduced fragmentation of these areas could help build more resiliency into some natural systems (see vol. 2, chs. 4 and 5).

Congress has increasingly linked policy direction to agency funding during the appropriation process. Congress could include requirements in its various appropriation bills that each of the agencies managing natural resources potentially affected by climate change provide Congress with its own evaluation of the agencies' preparedness to cope with a range of climate futures. The appropriation process may also be especially well-suited to encouraging agencies that implement climate-sensitive programs (e.g., agricultural disaster assistance, crop subsidies, and flood insurance) to develop long-term budget projections for those programs based on several future climate scenarios. In this way, a budget-conscious Congress can better inform itself early on about the potential costs of climate change for those programs.

■ Reauthorization Cycle

In addition to the annual appropriation cycle, congressional action is heavily influenced by the reauthorization cycles of major Federal programs. Congressional attention is not focused on all issues at once. Rather, at any given time, its attention is disproportionately focused, through its committees, on the major Federal programs for which current authorization is about to expire. The process of extending that authorization provides an opportunity to evaluate the workings of a program closely and to provide legislative direction for that program for a period of many years. Thus, at least with respect to changes in existing Federal natural resource programs, the best opportunities to implement the first steps recommended here are in the context of laws and programs that are about to be reauthorized.

Among these, the Clean Water Act is a high-priority target of opportunity (see vol. 1, box 5-C). Comprehensive revisions of that law have been proposed, and the act's wetland provisions are undergoing particular scrutiny. The reauthorization of the Clean Water Act provides a key opportunity to address one of the more important needs identified in this report-the need to achieve more effective integration of resource-management efforts across political jurisdictions. Comprehensive watershed planning (see vol. 1, ch. 5), which integrates wetland protection and restoration goals (see vol. 2, box 4-A), water-use-efficiency goals, strategies for controlling point-source and non-point-source pollution, and both water-quantity and water-quality concerns generally, could create the institutional capability and flexibility to anticipate and plan for climate change. Such planning could be especially valuable for finding creative ways to resolve current conflicts in which landowner and development interests chafe at restrictions on use of wetlands, while environmental interests decry the continued loss of wetlands (see vol. 2, ch. 4 and box 4-B).

Another major target of opportunity is the upcoming reauthorization of farm programs in the 1995 Farm Bill. The next reauthorization cycle could provide a forum for considering how to enhance farmers' flexibility and effectiveness in responding to a changing climate and how climate change may affect Federal expenditures on disaster assistance and farm commodity programs (see vol. 1, ch. 6).

New Targets of Opportunity

In addition to the reauthorization of existing laws, Congress regularly considers altogether new legislation creating programs for existing or new agencies of Government. A program of potentially great significance on the horizon is Interior Secretary Babbitt's proposal to create a National Biological Survey (see vol. 2, box 5-L). Legislation to establish the Survey has been introduced in both the House and Senate, and a National Research Council committee has been asked to offer advice on the formation and role of the Survey. The nature, mandate, resources, and overall purposes of the National Biological Survey, however, are still very much in the process of development. The bills introduced in Congress thus far to establish the Survey give only a very general description of its functions. Thus, there exists an opportunity to shape the content and direction of this new institution in ways that wouId be useful to the management of natural resource systems in a changing climate.

The rationale frequently offered by Secretary Babbitt for creating a National Biological Survey is its potential, by cataloging the biological resources of the Nation and monitoring their status and trends, to avert future "train wrecks,' that is, the disruptive and wrenching conflicts between conservation and development goals. A "train wreck' of another sort could take the form of severe adverse impacts on our natural resources from climate change for which we were unprepared. A National Biological Survey could help detect, evaluate, and prepare for that climate change. Thus, an important opportunity exists to structure the mission and capabilities of the Survey so that it can contribute to the early detection of indicators of climate change, a better understanding of the ability of organisms and natural communities to respond to climate changes, and the design and management of a system of preserves best able to achieve the purposes for which they were established. Careful congressional attention now to these details in the design of a National Biological Survey could yield major returns in the future (see vol. 2, ch. 5).

Existing Statutory Language

Of the many Federal statutes pretaining to the management of the natural resource systems discussed in this report, only one-the Coastal Zone Management Act (CZMA; P.L. 92-583)--explicitly addresses climate change and its potential consequences. The 1990 amendments to that law required that possible sea level rise resulting from climate change be anticipated and addressed in State coastal zone management plans (see vol. 1, ch. 4). Congress could extend this legislative precedent to other statutory arenas; here, we attempt to identify which statutes may be most appropriate for this.

None of the statutes governing the various natural resource systems discussed throughout the full report precludes the agencies responsible for their management from fully considering climate change. Existing grants of authority are sufficiently general and open-ended to allow an agency, on its own initiative, to examine the implications of climate change for the natural resources under its jurisdiction and to tailor its management of those resources accordingly. The question, therefore, is whether Congress wishes to supplement the existing legislative framework with explicit directives pertaining to climate change.

Several categories of legislation maybe especially appropriate for considering possible climate-change-related amendments. First among these are statutes, such as CZMA, that require long-range planning for the management of natural resources. For example, the Rangeland and Renewable Resources Planning Act of 1974 (RPA; P.L. 93-378) requires the preparation of a forest 'resource planning assessment' that looks

50 years into the future. Similarly, the Clean Water Act requires preparation of area-wide waste treatment plans that look two decades into the future, a planning horizon also found in the Pacfic Northwest Electric: Power Planning and Conservation Act (P.L. 96-501). In general, the longer the time frame over which management is to be planned, the greater the likelihood that climate change may affect the resources being managed. Thus, mechanisms to ensure that climate change is taken into) account when long-range plans are being developed and to ensure that plans can be revised as new information about the direction and magnitude of climate change becomes available are clearly desirable.

A second statutory area where it is especially important to ensure that potential climate change is considered is long-term public or private investments affecting natural resources. Examples include public land acquisition for parks, wildlife refuges, and the like (see vol. 2, box 5-C). Historically, such public land acquisitions have been viewed as permanent investments, with the intention of keeping the areas acquired in public ownership in perpetuity. The expectation implicitly accompanying these investments has been that the areas acquired would, with appropriate management, continue to provide the environmental and recreational benefits for which they were acquired indefinitely into the future. Climate change introduces a new uncertainty about the validity of this expectation. At the very least, it suggests the need for a more careful examination of whether particular acquisitions are, in fact, likely to continue to provide the environmental benefits that they provide today.

Somewhat similar are public or private investments in dams and other water-resource-development projects. Public projects are governed by the Water Resources Planning Act (P.L. 89-80) and private ones are licensed pursuant to the Federal Power Act (P.L. 102486). The implicit assumption underlying both has always been that hydrological models based on past climate will accurately predict future conditions as well. The possibility of climate change casts doubt on the continuing validity of that assumption and may warrant statutory revisions explicitly requiring water resource planning agencies and Federal regulators to factor climate change into their decisionmaking.

A third statutory arena relevant here includes those laws that require an evaluation of the expected environmental impacts of planned actions. Foremost among these laws is the National Environmental Policy Act (NEPA; P.L. 91-190); similar, though less far-reaching, laws include the Fish and Wildlife Coordination Act (P.L. 85-624) and the Endangered Species Act (P.L. 100-7O7). Under these and similar laws, expectations of the environmental impacts of planned actions may vary, depending on whether a constant or changing climate is anticipated. Legislative direction could provide useful guidance to agencies with respect to their duties to consider climate change possibilities in implementing their responsibilities (see, for example, vol. 2, box 5-D).

A fourth set of laws that warrant discussion consists of those that authorize research programs. The Clean Water Act and the Rangeland and Renewable Resources Planning Act are examples. As this report makes abundantly clear, there are many uncertainties about climate change, including its magnitude, its direction, and its impact on natural resource systems. Natural resource management will require research aimed at resolving many of today's uncertainties. Reflecting that need in the legislative description of the various research missions may serve o underscore the importance of this area of inquiry. Each resource chapter highlights important research options to consider.

Finally, the Science Policy Act of 1976 (P.L. 94-282), which established the Office of Science and Technology Policy (OSTP) and the Federal Coordinating Council on Science, Engineering, and Technology (FCCSET), could be amended to strengthen the ability of these offices to coordinate science and ecosystem management across agencies.[9] These offices have the authority to develop and implement coherent, government-wide science policy and have been the mechanism for coordinating several multi-agency programs. However, OSTP has not always been an active or influential player in the executive branch, and FCCSET lacks the authority to set priorities, direct policy, and fully participate in the budget process (17, 51). FCCSET acts largely as a fulcrum for coordination. Agency participation in FCCSET projects is voluntary, and FCCSET has no authority over how participating agencies spend their funds. Congress could amend P.L. 94-282 to change this. Similarly, the U.S. Global Change Research Act of 1990 (P.L. 101-606) could be amended to require periodic integrated assessment reports to be presented to Congress and to specify key participants in the assessment process.

SUMMARIES AND FIRST STEPS FOR EACH RESOURCE CHAPTER

▮ The Coastal Zone

The coastal zone is a complicated area that includes both human-made and relatively 'undisturbed" features, ranging from densely settled urban areas to cypress swamps (see vol. 1, ch. 4). Populations in coastal areas are growing faster than in any other region in the United States, and the construction of buildings and infrastructure to serve this growing population is proceeding rapidly. Consequently, protection against and recovery from hazards peculiar to the coastal zone, such as hurricanes and sea level rise, are becoming ever more costly (163). The combination of popularity and risk in coastal areas has important near-term consequences for the safety of coastal residents, the protection of property, the maintenance of local economies, and the preservation of remaining natural areas (see fig. 1-4).

The expected climate change impacts are likely to exacerbate problems that already plague the coastal zone (66). Sea level rise will substantially increase flooding and erosion in areas already vulnerable. Coastal storms-whether or not they increase in intensity or frequency under a changing climate-will have increasingly greater effects as sea level rises.

The coastal areas most vulnerable to the effects of climate change are those with low relief and easily eroded shorelines-such as those in the Southeast and Gulf Coasts-and those where the coastline is already subsiding, such as in Louisiana (52). Structures close to the ocean in low-lying areas are also vulnerable.

U.S. FISH AND WILDLIFE SERVICE

Barrier islands provide protection for coastal ecosystems and help stem erosion. In some cases, such as this barrier island near Tampa, Florida, these islands have been heavily developed, exposing many communities to the risks of serious damage from storms and high seas.

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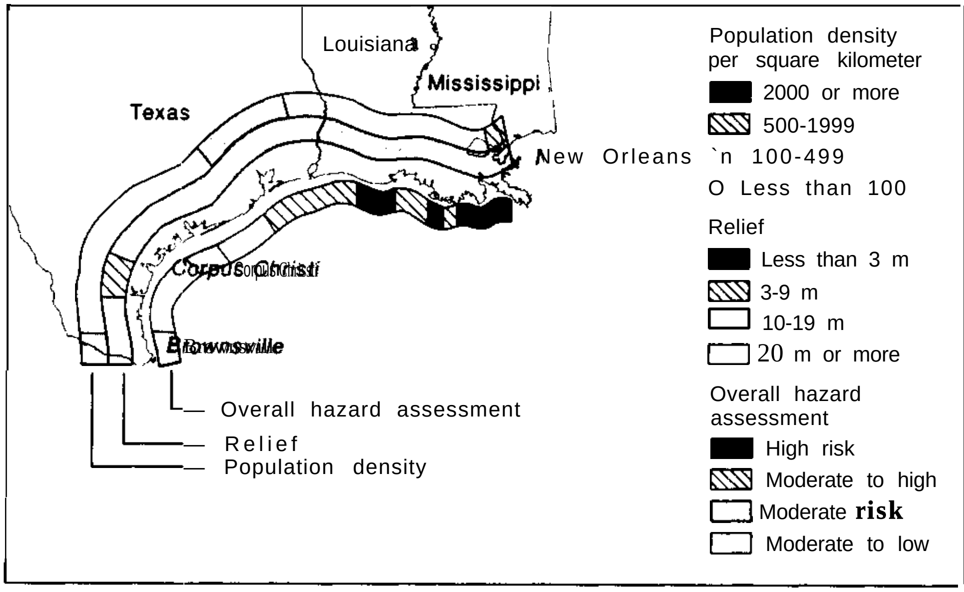
9 OSTP was established to "define coherent approaches for applying science and technology to critical and emerging national and international problems and for promoting coordination of the scientific and technological responsibilities and programs of the Federal -rots and agencies in the resolution of such problems," and FCCSET was established to "provide more effective planning and administration of Federal scientific, engineering, and technological programs" (P.L. 94-282, the Science Policy Act of 1976).

Figure f-4-An Assessment of Coastal Hazards: Texas and Louisiana



NOTE: To convert square kilometers to square miles, multiply by 0.624. To convert meters to feet, multiply by 3.280.

SOURCE: U.S. Geological Survey (USGS), "Coastal Hazards," In: National Atlas *of the United States of America* (Reston, VA: USGS, 1985).

Although development pressures in coastal areas are driven by many social and economic trends, government policies can influence the appropriateness, rate, quality, and location of development. The current system of allocating the costs of preventing or repairing climate-related damage in the coastal zone among Federal, State, and local governments and private entities encourages certain types of+ development, or at least does not discourage them (11). Climate change will likely add to the risks and costs of living in the coastal zone. It is essential that all stakeholders, such as property owners, understand them and that coastal development and preservation are guided by this understanding. The sooner policies are in place that encourage an adequate appreciation of risk, that offer sufficient incentives to take adequate precautions, and that attempt to overcome the organizational fragmentation that makes a unified approach to coastal climate change issues impossible, the easier and less costly adaptation to a changing climate is likely to be.

The Federal Government has an interest in promoting sound planning and public safety in an effective and efficient manner. Federal coastal zone policies can be improved in many ways to better guide the decisions of those living in coastal areas, and a suite of options for doing so is presented in volume 1, chapter 4. We focus on five general categories in that chapter: revamping the National Flood Insurance Program (NFIP), improving diaaster-assistance policies, revising the Coastal Barrier Resources Act (P.L. 97-348) and the Coastal Zone Management Act, changing beach-renourishment guidelines, and altering the U.S. Tax Code.

To help focus on where to start with responses to climate change in the coastal zone, some first steps that could be taken are listed below.

- **Revamp the National Flood Insurance Program.** The National Flood Insurance Program could be revised to provide stronger incentives to reduce the potential costs associated with high-risk development in coastal areas. Congress has been considering revising the NFIP for several years, and bills to do this have been introduced in both the House and Senate. H.R. 62, the "National Flood Insurance Compliance, Mitigation, and Erosion Management Act of 1993, " contains provisions that partially address some of the NFIP improvements that maybe desirable. Most pressing is the need to adequately address erosion along the coast. Erosion losses will increase with rising sea levels. The Federal Emergency Management Agency does not now have the authority to map erosion risks or to reflect such risks in insurance premiums, and as a consequence, information and incentives to avoid development in eroding areas are inadequate. Also, it seems especially desirable to increase insurance premiums after multiple claims are made on properties in high-risk areas subject to repeated flooding.
- **Improve disaster assistance.** Several bills have also been introduced in the 103d Congress to revise disaster-assistance policies and regulations. More stringent disaster mitigation by States and localities could be required, which could hold down future costs to the Federal Government. This could be accomplished by more strongly tying disaster assistance to adoption of mitigation measures. H.R. 935, the "Earthquake, Volcanic Eruption, and Hurricane Hazards Insurance Act of 1993, " for example, would establish minimum criteria for reducing losses, recommends such measures as fiscal incentives to reduce losses, provides for low-interest loans or grants to retrofit facilities vulnerable to hurricanes, and provides guidelines for establishing actuarial premium rates for disaster insurance. S. 995, the "Federal Disaster Preparedness and Response Act of 1993,' would establish, among other things, a grant program and accompanying performance standards to help States prepare for, respond to, and recover from major disasters.
- **Strengthen coastal zone management.** The Coastal Zone Management Act will be up for reauthorization in 1995, and this provides an opportunity to require stronger State controls on risky development. Such controls could include, for example, an erosion-setback program (already adopted by several States), re-restrictions on construction of immovable buildings, a relocation-assistance program, restrictions on rebuilding damaged or destroyed structures in high-risk locations, and adoption of minimum coastal-construction standards. All of these controls would add some degree of protection against sea level rise and flood or storm damage. Another possibility for reducing risks of living on the coasts would be to encourage States to adopt coastal-hazards-management programs. These could be overseen jointly by the National Oceanic and Atmospheric Administration and the Federal Emergency Management Agency.
- **Promote public education.** The public generally is not well-informed about the risks associated with living in coastal areas, and this lack of awareness has led and will continue to lead to large public and private expenditures. H.R. 935 provides one possibility for expanding public education. The act authorizes education programs and provides funds to States to implement them through a self-sustaining mitigation fund. The private sector, particularly the private insurance industry, could also play an important role in increasing awareness of coastal hazards.
- **Require increased State and local contributions to beach-nourishment operations.**

Most benefits of the U.S. Army Corps of Engineer's beach norishment and shoreline-protection projects are realized at the local or regional level, yet these projects are often heavily subsidized. In most instances, the Federal share is 65 percent. Greater State and local contributions could be required, both for initial construction and for maintenance, and Federal funding could be made conditional on adoption of stronger mitigation measures. These adjustments would tend to increase the interest of local governments in acting to limit community exposure to coastal hazards.

Water Resources

Many factors are straining the Nation's water resources and leading to increased competition among a wide variety of different uses and users of water (see vol. 1, ch. 5), Human demands for water are increasingly in conflict with the needs of natural ecosystems, and this has led to significant water-quality and water-quantity problems (see vol. 1, box 5-B). In addition, water infrastructure in many urban areas is aging.

Although it is unclear exactly how climate change will affect water resources, climate change has emerged as another important factor to consider in water resource planning. Changes in water availability as a result of climate change could further affect already overburdened systems, and changes could occur in the frequency, duration, and intensity of floods and droughts (105). The areas that are most vulnerable to climate change are, not surprisingly, places that are already experiencing stressed water resources (see fig. 1-5), such as many parts of the Southwest and South Florida; the central part of the country, which most models predict will become hotter and drier; and areas where competition for water is expected to increase.

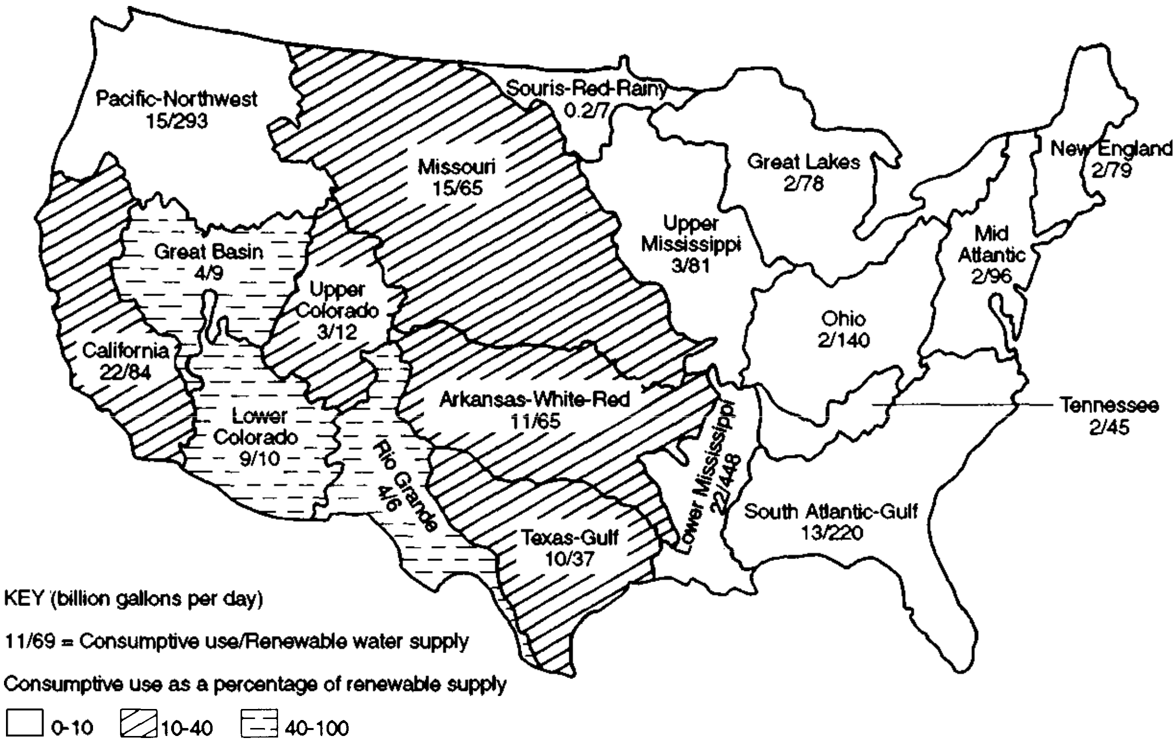
The country faces a huge challenge in adapting its water resource systems to the many current and potential stresses. The numerous impediments to this adaptation include the fact that traditional engineering solutions for developing additional water supplies-such as dam construction-have become prohibitively expensive and politically less acceptable because the best sites have already been developed. Federal agencies' responsibilities for water often overlap or conflict, and coordination among different levels of government on water issues is often inadequate (166) (see vol. 1, box 5-F). Many institutional arrangements for the management and allocation of water resources are rigid and inefficient, making them ill-equipped to cope well with water scarcity. And there are very few incentives to conserve water.

Water resource planning is a complex political, economic, sociological, scientific, and technological endeavor, so adaptation to change will not be straightforward. In encouraging adaptation to changes in water resources caused by climate change, the Federal Governrnent, in cooperation with State and local agencies, should focus on encouraging five types of activity: improving demand management (e.g., through pricing reform and conservation); improving supply management (e.g., through improving coordination, jointly managing ground- and surface-water supplies, and improving the management of reservoirs and reservoir systems); facilitating water marketing and related types of water transfers; improving planning for floods and droughts; and promoting the use of new analytical tools that enable more efficient operations.

The following first steps toward improving water resources planning and management—selected from a longer suite of options presented in volume 1, chapter 5-are intended to both relieve existing stresses and make sense for climate change.

- **Improve extreme-events management.** Despite all efforts to date, both floods and droughts continue to cause significant losses to human and natural systems (143, 200). Greater coordination of the many agencies with flood- or drought-related re-

Figure 1-5-Water Withdrawals and Consumption in the Coterminus United States, 1985



NOTE: To convert gallons to liters, multiply by 3.785.

SOURCE: Adapted from W. Solley, R. Pierce, and H. Perlman, Estimated Use of Water the *United States* in *1990,* USGS Survey Circular 1081 (Washington, DC: U.S. Geological Survey, 1993),

sponsibilities is needed. Congress could direct the executive branch to create high-level coordinating bodies, such as an inter-agency drought task force and a national flood-assessment board. Such bodies could be given the responsibility to develop a national drought policy and to establish national goals for floodplain management. The "National Flood Insurance Compliance, Mitigation, and Erosion Management Act of 1993" (H.R. 62) calls for establishment of a flood-insurance task force. This bill could also be broadened to create a more comprehensive flood-assessment board.

- Make it easier to manage reservoirs on a basin-wide level. Operating reservoirs within the same basin as a single system rather than individually (as is often the case) could greatly improve the efficiency and flexibility of water-quantity management. New legislation, perhaps as part of the next omnibus water bill, could grant the Army Corps of Engineers and the Department of the Interior's Bureau of Reclamation greater flexibility to manage their reservoirs basin-wide and thus encourage development of a more integrated approach to water-quality, wetland, flood, and drought management.
- Support water marketing. As long as adequate attention is given to protecting all affected parties, water markets could provide an efficient and flexible way to adapt to various stresses, including a changing climate. It would be very useful for Congress to clarify reclamation law on trades and transfers and define the Federal

Government's interest in facilitating the creation of markets (193). Congress could urge the Department of the Interior to provide stronger leadership to assist with water transfers, and water marketing could be thoroughly evaluated as part of the Western Water Policy Review, authorized in late 1992.

- Promote the use of new analytical tools. Further development dissemination, and use of new modeling and forecasting tools could greatly enhance water resource management. Some current analytical efforts have not been adequately funded, and the most advanced tools now available are not yet being used by many States or water utilities. Small investments in promoting dissemination and use of these tools today could save substantial sums later. Section 22 of the Water Resources Development Act of 1974 (P.L. 93-251) authorizes funding for training and technical assistance to States and could be used to promote the adoption of the new tools. Congress could also consider providing funds to develop or refine tools that incorporate climate uncertainty into traditional hydrologic analyses.
- Promote demand management. The upcoming reauthorization of the Clean Water Act is one potential target of opportunity for improving water-use efficiency (see vol. 1, box 5-C). Congress could consider making conservation projects eligible for the State revolving-fund loans created under the act to fund wastewater treatment plants. The Federal Government could set an example by adopting efficient water-use practices in its own facilities. The Energy Policy Act of 1992 (P.L. 102-486) requires that Federal facilities adopt conservation practices to the extent practicable, but it concentrates primarily on energy conservation. A technical-adjustment bill to the Energy Policy Act could be considered in the 103d Congress and would provide a way to clarify and underline congressional intent toward water conservation in Federal facilities.
- Expand the scope of the Western Water Policy Review. With the enactment of Title 30 of the Reclamation Projects Authorization and Adjustment Act of 1992 (P.L. 102-575), Congress authorized the Resident to oversee a major water-policy study. Title 30 directs the President to undertake a comprehensive review of Federal activities that affect the allocation and use of water resources in the 19 western States and to report findings to appropriate congressional committees by the end of October 1995 (190). Climate change is not mentioned as a factor motivating the Western Water Policy Review, but the study could provide an opportunity to assess more fully how climate change may affect water resources and to evaluate policy options that might help with adaptation to a warmer climate. Congress could expand the scope of the Review beyond the West, or it could authorize a similar follow-on study of eastern water issues. The Review could also provide an opportunity to explicitly consider land-use practices and water resource issues jointly. The relationship between the two is close, and there appear to be significant opportunities to improve both water-quantity and water-quality management by improving land-use practices.

Agriculture

Agriculture in the United States is an intensively managed, market-based natural resource. Throughout the world, agriculture has adapted continuously to the risks associated with normal climate variability, just as it has adapted to changes in economic conditions. The American agricultural sector will undoubtedly make further adaptations in response to climate changes, with market forces rewarding and encouraging the rapid spread of successful adaptation (30, 41, 148). Just what these adaptations will be and what public actions could be taken to encourage them are addressed in detail in volume 1, chapter 6, of this report.

The possible effects of climate change on agriculture are difficult to predict. Agricultural productivity is likely to be affected worldwide, which would lead to alterations in the regional distribution and intensity of farming (1, 188). The range over which major U.S. crops are planted could eventually shift hundreds of miles to the north (13, 150) (see vol. 1, box 6-C). For American farmers, already facing increasingly competitive and growing world markets, any relative decline in productivity compared with the rest of the world would mean lost markets (40). A significant warming and drying of the world's climate might lead to an overall decline in agricultural yields (75, 150). Consumers would bear much of the cost through higher food prices or scarcities. Some individual farmers might still benefit through locally improved yields or higher prices; others might suffer because of relatively severe local climate changes. Rapid geographical shifts in the agricultural land base could disrupt rural communities and their associated infrastructures.

If the United States wants to ensure its competitive position in the world market and meet the growing demands for food without higher prices, public efforts to support the continued growth in agricultural yields remains necessary. Climate change adds to the importance of efforts to improve the knowledge and skills of farmers, to remove impediments to farmer adaptability and innovation, and to expand the array of options available to farmers (157). Efforts to expand the diversity of crops and the array of farm technologies insure against a future in which existing crop varieties or farming systems fail (137) (see vol. 1, box 6-H). Efforts to enhance the adaptability of farmers--to speed the rate at which appropriate farming systems can be adopted-lower the potentially high costs of adjustment to climate change.

JSDA AGRICULTURAL RESEARCH SERVICE

This soybean field shows the devastating effects of droughts. The farmer indicates how tall soybean plants would normally be. Warmer climates could lead to an increase in both nurnber and severity of droughts.

Impediments to adjusting to climate change are numerous (see vol. 1, box 6-I). Water shortages will probably limit the potential for compensating adjustments in certain regions. The uncertainty of climate change makes effective response difficult, as do limitations on the availability of suitable crops and agricultural practices. The decline in the Federal Government's interest in agricultural research and extension is also a problem (138, 174); more-vibrant research and extension programs could enhance adaptability.

Certain agricultural programs may increase the costs associated with a changing climate (90). Because the commodity programs link support payment to maintaining production of a particular crop, they could inadvertently discourage adjustments in farming. Disaster-assistance programs may become increasingly costly under a harsher climate, and, if not well designed, may tend to discourage farmers from taking appropriate cautionary actions to reduce exposure to climate risks. Restriction on the marketing of conserved water may limit the incentive for efficient use of scarce water resources.

The most pressing tasks concerning agriculture and climate change that the Federal Government should undertake are: improving technology and information transfer to farmers in order to speed adaptation and innovation in farm practice; removing the impediments to adaptation created unnecessarily by features of commodity support and disaster-assistance programs; and supporting research and technology that will ensure that the agricultural sector can deal successfully with the various challenges of the next century.

The Government could organize its approach around the following first steps, which should increase the ability of the farm sector to adjust successfully to a changing climate.

- Revise the commodity support programs. Congress addresses farm issues every 5 years in omnibus farm bills, with the next one likely to be debated for passage in 1995. The annual budget-reconciliation process and agricultural appropriations bills offer intermediate opportunities for revisions in commodity support programs. commodity support payments are linked to the continued production of a single crop. If a farmer significantly changes crops, support payments will be reduced. This link discourages the responsiveness of farmers to changing market and climate conditions. The cumulative economic costs of even temporary delays in adjusting to climate change might prove to be large. Congress should consider breaking the link between farm support and the production of a single crop. A further increase in flex acreage (an amount of land that can be shifted to new crops with little penalty) or other more substantial revisions in the commodity support programs that would allow greater flexibility in crop choice (42) could be considered in the 1995 reauthorization of the Farm Bill. These changes would increase the ability of farmers to adapt to climate change.
- Encourage research and development in computerized farm-management systems. The competitiveness of the farm sector will increasingly depend on advances that improve the efficiency of U.S. farmers-rather than on further increases in intensity of input use. Computerized farm-management systems include land-based or remote sensors, robotics and controls, image analysis, geographical information systems, and telecommunications linkages packaged into decision-support systems or embodied in intelligent farm equipment. Such systems will be increasingly important to the farmer's ability to increase yields, control costs, and respond to environmental concerns. The U.S. Department of Agriculture's Agricultural Research Service already provides leadership in this area and has proposed an "Integrated Farm Management Systems Research' program that would provide for the development and broader use of technologies that have the potential to greatly enhance the efficiency of farming and to increase the flexibility with which farmers can respond to climate conditions.
- Use the 1995 Farm Bill to modify disaster-assistance programs. Since the late 1970s, Congress has been considering how to best structure the crop-insurance and disaster-payment programs (20, 21). After a flurry of proposals and studies before the passage of the 1990 Farm Bill, the programs were left essentially unchanged. Major revisions are likely to be considered in the 1995 Farm Bill. The best option for revising these programs remain unclear. For the purpose of preparing for climate change, any program that provides a greater incentive for farmers or local communities to reduce their exposure to risk should lessen the potential for large-scale future losses and encourage adaptation to changing climate risks. Features of a restructured system might include: defining disasters formally,

with assistance provided only for statistically unusual losses; eliminating either crop insurance or disaster payments (or merging the two programs) so that one does not undercut the incentives to participate in the other; limiting the number of times a farmer could collect disaster payments; and requiring farmers or farm communities to contribute to a disaster-payment fund, thus providing a greater incentive to reduce exposure to risks.

Wetlands

More than half of the Nation's wetlands have been destroyed by activities ranging from agriculture to flood-control projects to urban development. Roughly 5 percent of the lower 48 States is currently covered by wetlands (see vol. 2, ch. 4). They provide diverse products of considerable commercial value, playing a key role in the production of goods such as finfish, shellfish, fur, waterfowl, timber, blueberries, cranberries, wild rice, and peat. Wetlands also nurture biological productivity, slow surface-water flows, and transform nutrients and toxic chemicals. Wetlands are key to the harvest of 75 percent of the Nation's fish and shellfish and harbor about one-third of the Nation's threatened and endangered species (83).

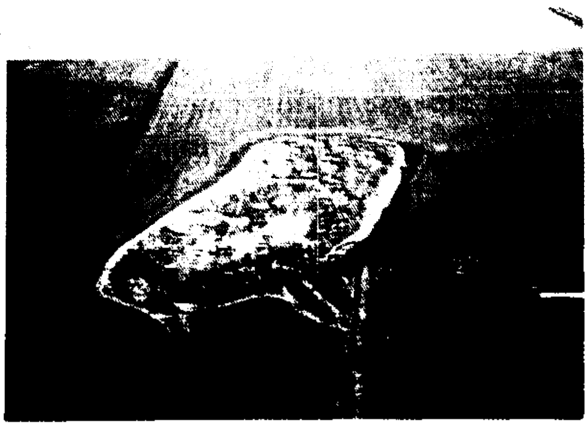
As a result, in 1989, the Federal Government embraced the policy goal of no net loss of wetlands-any destruction of wetlands should be offset by an equivalent restoration or creation of wetlands (28, 184). Steps to achieve this goal, however, have not been fully implemented. Part of the problem is that no single Federal statute is directed at protecting, restoring, and acquiring wetlands, and there is no coordinated effort to monitor and evaluate wetlands. Different authorities with different goals are scattered across many Federal and State agencies, and the criteria they use for decisionmaking are somewhat inconsistent. Federal policies have sometimes failed to discourage--and sometimes have encouraged—wetland destruction (179). Few programs for wetland acquisition and restoration address the possibility of climate-induced alteration of wetlands.

Climate change is likely to accelerate the loss of wetlands, especially of the following highly vulnerable types: coastal wetlands, depressional wetlands in arid areas (i.e., inland freshwater marshes and prairie potholes), riparian wetlands in the arid West and Southwest, and tundra wetlands. Coastal wetlands may be drowned by a rising sea or altered by changing salinity (123, 194, 198). Depressional wetlands are susceptible to the lowered water tables that will likely result from the higher temperatures, increased evaporation, and decreased summertime precipitation predicted for these already dry areas. Riparian wetlands in the arid West, which rely on water flowing through rivers and streams, could also be threatened by drier conditions. Tundra areas in Alaska may shrink as increased temperatures allow the permafrost to thaw and drain.

Whether or not a no-net-loss goal can be achieved as the effects of climate change become more pronounced, the goal remains a useful focal point for policy makers (114). Wetlands are a diminishing resource, and the Federal Government could play a lead role in ensuring that wetlands survive climate change by adopting the following objectives: protect existing wetlands, restore degraded or converted wetlands, facilitate migration (e.g., the upslope movement of coastal wetlands as sea level rises), and improve coordinated management and monitoring.

Given the available policy levers (regulation and acquisition, incentives and disincentives, and research), limited money to fund programs, and the level of scientific understanding of the impacts of climate change on wetlands, we identified the following strategies as first steps to use in responding to climate change and the threats it poses to wetlands. Additional options are assessed in volume 2, chapter 4.

U.S. FISH AND WILDLIFE SERVICE



Prairie potholes, like these in North Dakota, serve valuable storm-water-retention functions and provide breeding and stopover habitat for migratory waterfowl. Agricultural development, encouraged in part by Federal subsidies, has eliminated many of these wetlands. Climate change rnay pose further risks if moisture declines or if farming intensifies with a warming in these northern lands.

- **Revise the Clean Water Act. The act is up now for reauthorization, and it could be revised to improve wetland protection (169). This could be done through minor revisions or through transforming the act into a broad wetland-protection and watershed-management act. For example, the mitigation requirements could be clarified to ensure that lands set aside for protection or restoration more than compensate for wetlands that are destroyed. Congress could establish uniform standards for mitigation activities and require that restoration projects be monitored and evaluated for success in meeting these standards. At a broader level, Congress could devise a mechanism for coordinated management of water quality and wetland resources at a regional or watershed level. For example, regulations covering non-point-source water pollution might be linked to wetland protection, allowing wetland restoration or protection in exchange for relaxation in pollution-control requirements (127).**
- **Develop and implement a priority plan to coordinate wetland protection across agencies. Direct Federal agencies to develop and implement uniform regional plans guiding wetland protection, acquisition, mitigation, and restoration and to coordinate the designation of wetlands deemed high priority for protection or restoration. These priority plans could be built on existing plans under various agencies (e.g., the Army Corps of Engineers, the Environmental Protection Agency, DOI'S Fish and Wildlife Service, and the U.S. Department of Agriculture) that now set priorities for wetland management and acquisition. With better coordination and guidance and a watershed-management focus, existing programs could accomplish wetland protection more efficiently.**
- **Ensure that all Federal policies and incentives are consistent with wetland protection. Congress could ensure that all Federal policies and incentives are consistent with wetland protection, reviewing Federal programs to find and eliminate those that offer incentives to destroy wetlands and to perhaps bolster programs that encourage wetland protection. For example, the Coastal Barrier Resources Act (P.L. 97-348, as amended) might be extended to include coastal wetlands; funding for the Wetlands Reserve Program might be restored to at least authorized levels and targeted to wetlands in high-priority areas. The Fish and Wildlife Service could be required to complete and issue the report on the impact of Federal programs on wetlands that was mandated in the Emergency Wetlands Resources Act of 1986 (P.L. 99-645).**
- **Conduct research, development, monitoring, and evaluation in key areas. A new National Biological Survey at the Department of the Interior could incorporate wetland monitoring as part of its mission (see vol. 2, ch. 5). Relevant agencies should be encouraged to include wetland research in**

their component of the U.S. Global Change Research Program (USGCRP).

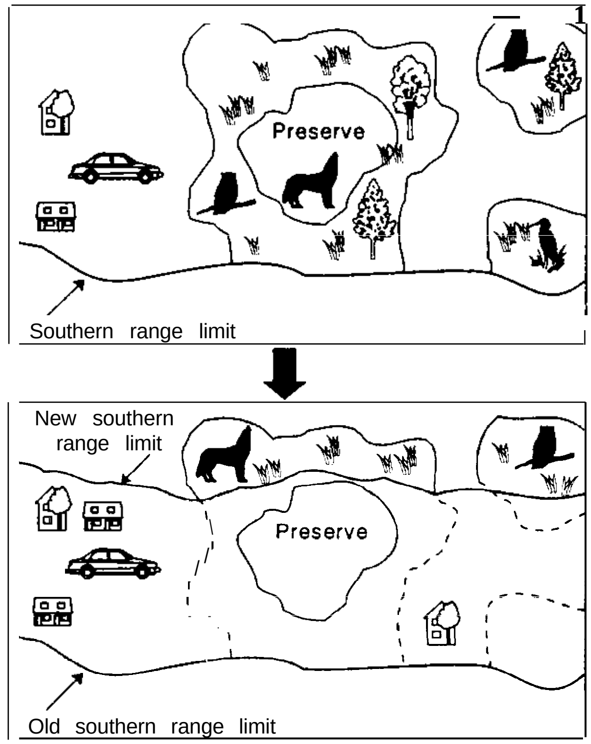
Federally Protected Natural Areas

Over 240 million acres of land have been set aside by the Federal Government to protect some part of nature for generations to come. These lands represent and protect the best of the Nation's natural heritage and have become a source of national pride. Chapter 5 of volume 2 focuses on National Parks, Wilderness Areas, and National Wildlife Refuges, which comprise the bulk of the Federal lands held primarily for nature conservation.

Because a variety of human activities has altered or degraded the habitat for many species, federally protected natural areas have become repositories for the Nation's rarest species and sites for conserving biological diversity (181, 185). Protected natural areas are also subject to increased stress from activities that occur both within and outside their boundaries. Natural areas are being effectively dissected into smaller and smaller parts in some places--especially in the East-leaving them more vulnerable to other stresses that could degrade habitat quality and ecosystem health (103).

Under climate change, the climate "map' that has helped to shape natural areas will shift while the boundaries that define the management and degree of protection for natural areas will remain fixed (see fig. 1-6). As a result the biological makeup of the protected natural areas will change. Some may become incapable of providing the benefits or serving the functions for which they were originally established, such as maintaining their unique or distinctive character, providing protection for rare species and other biological resources, and maintaining the quality or availability of other services, such as nature study or certain kinds of recreation (see vol. 2, box 5-B).

Figure l-S-Preserves and Climate Change



NOTE: As climate changes, the preferred range of many species may shift, leaving preserves dramatically changed.

SOURCE: Office of Technology Assessment, 1993.

Certain general characteristics of protected natural areas may make them more vulnerable to climate change, such as being small, isolated, fragmented, or already under considerable stress, and containing sensitive species or ecosystems, such as coastal, alpine, or Arctic ecosystems or midcontinent wetlands (67, 133, 188). If climate change leads to accelerated habitat loss or proceeds so quickly that some species cannot adapt quickly enough, species loss may accelerate, and overall biodiversity will decline (29, 196).

Even if species can move fast enough, adaptation by migration may be difficult because in many places, the landscape has been sectioned off into small pieces. Some natural areas are islands in the middle of extensively developed areas. Geographic fragmentation may limit the ability of

Box I-G-Climate Change in Alaska: A Special Case

Nowhere in the United States does there remain such a vast expanse of land so undisturbed by human activity as in Alaska. Because of its distinctive character, pristine conditions, and abundant natural resources, Alaska has become a national treasure. Nearly 66 percent of Alaska's land base is protected in wilderness areas, National Wildlife Refuges, National Forests, or public lands administered by the Bureau of Land Management (BLM). Alaska contains some 170 million acres (69 million hectares)[1] of wetlands (over 60 percent of the Nation's total) and 330 million acres of boreal forest. Alaskan plants and animals withstand some of the harshest environmental conditions in the world and many are unique to polar climates. Although human activities are to some extent adversely affecting this remote environment, it remains the most wild place in the United States and is rightly referred to as our "last frontier."

The unique characteristics of Alaska-the natural resources, the wildlife, and the pristine, harsh environment-affect nearly every aspect of life, including the culture and industry of those who live here. For example, traditions of the indigenous communities are deeply rooted in t he distinctive wildlife and vegetation of Alaska. Many indigenous communities, such as the Inupiat Eskimos of Alaska's North Slope, still rely on wildlife and natural vegetation for subsistence. The bowhead whale is central to their culture. The whales are a major food source and the hunts are a community tradition. Caribou and fish are other staples for Inupiats. Athapaskan Indians, who reside mostly in the boreal forest of interior Alaska, rely heavily on the plant life there for food, housing materials, and heating fuels (120). Fish such as salmon and whitefish are primary elements of Athapaskan subsistence, and caribou and moose are important sources of food anddothing(120).

Alaska's economy is also deeply rooted in its abundant natural resources, with oil and gas, fishing, and tourism providing the base for the economy. Nearly 65 percent of the State's revenue comes from oil and gas exploration or development. Two of the largest oil fields in North America (Prudhoe Bay and Kuparuk fields) are located near Alaska's North Slope and provide the economic base for much of that region. Alaskan waters are also sites of some of the world's most productive fisheries. The Bering Sea has the biggest fishery in the United States; it is among the biggest in the world. In 1990, Alaska's fish harvest (mostly salmon, king crab, halibut, shrimp, and scallops) surpassed any other State's, with more than 5.4 billion pounds (2.4 billion kilograms)[2] of seafood harvested-half of all seafood harvested in the Nation. The seafood industry is also Alaska's largest private-sector employer, employing 23 percent of the State's work force. In addition, Alaska's vast expanse of rugged land and abundant wildlife have made tourism a growing and important industry there. Visitors to Alaska spent almost $1 billion in 1989, the third largest source of income in the State. With 13,500 workers in tourist-related industries, tourism is second only to fisheries as a source of employment?

Because climate changes resulting from rising atmospheric carbon dioxide (CO_2) are expected to be especially pronounced in Alaska and other high-latitude regions, Alaska may provide an "early warning" of initial climate effects. In very general terms, Alaska can expect to see increased average temperatures, increased precipitation, and melting of sea ice. The rate and ultimate severity of the climate changes is at present unknown (67). In addition, little is known about the sensitivities of wildlife, vegetation, ecosystems, indigenous cultures, or the economy to any potential climate changes.

Warmer temperatures in polar regions are expected to lead to some melting of sea ice. A recent study of climate change effects on the Canadian Beaufort Sea determined that, based on a doubling of atmospheric CO_2 the open-water season could increase from an average of 2 months to 5 months, the extent of open water could increase from about 100 miles (160 kilometers)[4] to 300-500 miles, and maximum ice thickness could decrease

1 To convert acres to hectares, multiply by 0.405.

2 To convert pounds to kilograms, multiply by 0.454.

3 P. Carlson, Alaska Division of Toursim, personal communication, September 1993.

4 To convert miles to kilometers, multiply by 1.609.

by 50-75 percent (102). Shoreline erosion could increase significantly with a longer open-water season. Overall biological productivity is also expected to increase in parts of the Bering Sea with an increase in temperature and change in ice cover. Because of the drying effects of warmer temperatures, there could be an increase in the frequency and extent of fires. Over the past three decades, fires in Alaska have increased due to warmer and drier conditions. More fires under climate change could expand the extent of early successional vegetation favored by moose, beavers, Arctic hares, sharptailed grouse, and other wildlife species. However, fire may adversely affect the lichen supply in spruce forests--an important food for caribou in winter.

The most profound consequence of warming in Alaska and other polar regions maybe the exacerbation of global climate change through the release of carbon from the permafrost of the Alaskan tundra and boreal forests. Worldwide, tundra and boreal forests contain nearly a third of the world's soil carbon. Thawing of the permafrost, and the resulting decomposition of organic material, could release huge quantities of methane (CH_4) and $C0_2$ into the atmosphere and contribute to accelerated warming (67).[5] Climate warming may also be exacerbated by melting of the vast expanse of ice and snow that now reflects away considerable incoming heat. Little can be done to stem the thaw and resulting secondary climate impacts, except to slow warming by reducing human-made greenhouse gas emissions.

Potential Losers

Indigenous cultures--Alaska's indigenous, subsistence communities could be at risk under climate change. Thawing of the permafrost is likely to affect supported structures such as pipelines and bridges, and roads may be threatened if thawing weakens the soil. Many indigenous peoples use the permafrost for food-storage cellars, so warming may threaten their ability to preserve food during summer months. Hunting the bowhead whale, an ancient and sacred tradition for many indigenous communities on the North Slope, is linked to the extent of sea ice. Melting of the sea ice will likely change the whale's migration and affect access to the whales by indigenous hunters.

Plants and animals--early half of the world's peatlands (tundra) are in North America, with nearly a third of these in Alaska. Evena2'F (1 ºC) warming could lead to forests replacing alpine tundra on many mountains and islands (122). Some tundra species unable to adapt to climate change might decline. Caribou populations depend on lichens for food. The distribution of lichens is sensitive to the amount and extent of snow cover, which will change under a warming climate. Furthermore, because caribou calving is linked to vegetation produced during early snow melt, changes in the timing of the melt could disrupt calving.

Some 25 species of marine mammals regularly use Alaskan waters. The marine mammals most likely to be adversely affected by climate change are pinnipeds (seals and walruses) that winter primarily in t he Bering Sea have regular contact with ice, and are closely associated with the continental shelf or shelf edge. These include spotted and ribbon seals, which may suffer from increased competition with other species and reduced habitat, and Pacific walruses and bearded seals, which are ice-associated bottom feeders and are therefore tied to the seasonally ice-covered continental shelves. Both the beluga and bowhead whales are associated with sea ice, but they may not be significantly affected by melting because they do not depend on ice cover to protect and nurture their newborn.

Perhaps the biggest unknown impact of climate change is how it will affect fish populations and the fishing industry. Variations in stock size and species abundance appear to be correlated wit h periodic variability of ocean temperature, but are not completely understood. For example, huge fluctuations in groundfish stocks occur now.[6] Many scientists believe that overfishing will remain the primary concern for Alaskan fisheries (122). However,

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5 Recent measurements Indicate that the tundra of the North Slope of Alaska has in fact Changed from a "sink" to a "source" of $C0_2$ with the warming trend seen in Alaska over the past few decades (125).

6 V. Alexander, Dean, School of Fisheries and Ocean Science, University of Alaska at Fairbanks, personal communication, May *27, 1993.*

(Continued on next page)

Box 1-G--Climate Change in Alaska: A Special Case-(Continued)

considering the importance of fishing to the Alaskan economy, the potential for loss under climate change is significant

Potential Winners

0il and gas industry-Reduction of the sea ice could allow the use of less expensive offshore structures and would reduce the costs of marine transportation. Some speculate that the opening up of the Northwest Passage would offer a shortcut for shipping from Europe to the Pacific Rim, but Alaskan ports probably would not participate significantly in this traffic.

Plants and animals-in general, plant life is likely to benefit from an increase in temperature, though the composition of forests and other vegetated areas will likely change. Some boreal forest species, such as white spruce and birch, are likely to expand northward. Others, such as red and yellow cedar, may be less able to migrate because of the rugged terrain, low genetic variability, and slow dispersing ability. Some migration is already happening--white spruce ranges have been expanding over the past 40 years. Expansion of white spruce into boreal forests may eventually be important for timber harvests.

Most wildlife species, including polar bears, moose, muskoxen, mountain sheep, most marine mammals, and many birds (e.g., grouse, raptors, owls, and migratory birds), will likely benefit from increased temperatures and increased productivity in vegetation. These benefits might be stemmed by losses of tundra wetlands, increases in disease spread, or changes in species assemblages that would result in changed predation patterns. Most birds will likely benefit from having more forage, more insects, and a longer season during which to rear their young. Omnivores such as bears should respond favorable to a changing climate because of the longer availability of green vegetation in the spring. Other forbearers and carnivores should increase in response to larger prey populations unless they are controlled by hunting, trapping, or other human activities.

Tourism-Higher temperatures are likely to benefit the tourism industry, although vigorous advertising by the State has almost certainly had more impact on the industry in recent years than has its climate. Increased wildlife populations will probably attract more hunters, hikers, and campers. However, increased tourism could also mean more impacts on the environment that is so important to indigenous, subsistence communities.

species to find new habitat-they may have no place to go (34).

Natural areas in the West are currently much larger and much less fragmented than they are in the East. However, the institutions that manage these lands are designed to manage only their own parcels-in isolation—and are not encouraged to consider the often more extensive natural ecological system. This compartmental approach to management, or *institutional fragmentation,* may prevent effective solutions to problems that transcend individual management parcels, such as those posed by climate change (64, 92).

The main challenge for policy is to maintain the high value of the system of natural areas while realizing that climate change may affect the very factors that make natural areas valuable: character, species protection, and environmental services. The ideal response to this challenge might be some combination of three general management approaches: 1) maintain species where they are today, 2) help species migrate through more intensive management, and 3) acquire lands that will be valuable under a changed climate. However, the lack of adequate knowledge and information precludes the full implementation of either approach now.

It is difficult to predict how climate change will affect natural areas and how they will respond. This lack of knowledge limits the ability to help natural areas adapt. We do not know which species are most sensitive to climate change, which could be saved, or how to recreate habitats or entire ecosystems elsewhere. The limited success with restoring populations of endangered species illustrates how little is known about restoring species and their natural habitat. In addition, we do not know what lands will be most valuable as preserves under climate change. We do not even know all of the species and kinds of ecosystems currently under formal protection in preserves today.

The most useful approaches that the Federal Government could take to facilitate adaptations to climate change in natural areas fall into two categories: information gathering (including research, inventory, and monitoring options) (115, 171), and managing natural areas now to minimize the impediments to adaptation and to increase their resiliency. The second category includes taking direct Federal action to influence the management of natural areas, establishing incentives to private landowners to encourage conservation under uncertainty, and promoting larger-scale management through more partnerships among agencies, communities, and governments. A variety of options that address these needs are assessed in volume 2, chapter 5.

Because money to implement every policy option and the scientific understanding of how climate change will affect natural areas are limited, we have identifed some strategies that represent inexpensive or useful frost steps for facilitating adaptation to climate change in natural areas. These options meet at least one of several criteria: they will take a long time to complete; they address "front-line," or urgent, issues that need attention before informed policy decisions can be made; they can be approached through mechanisms that are already in place or through efforts already under way; and/or they have benefits in addition to those that help prepare for climate change. In some cases, a near-term legislative action will provide a target of opportunity to pursue these options.

- Use the National Biological Survey (NBS) to assess ecological inventory and monitoring needs. Future strategies to protect natural areas and their resources will require a national picture of current biological resources and the extent of the protection of-or the threat to-these resources. A national inventory and monitoring program would be particularly beneficial in supporting efforts to protect endangered species and biodiversity. DOI'S proposed new National Biological Survey presents an opportunity to implement some of these activities (131, 132, 188). Congress could ask NBS to initiate a nationwide inventory and monitoring program, synthesize ecological and biological information for managers and planners, establish a mechanism for facilitating regional-level research and management, and develop a priority plan for expanding protection of natural areas.
- Support basic research on key gaps in our understanding of ecosystems. This research would include work on species sensitivity to climate change, restoration and translocation ecology, the design and effectiveness of migratory corridors or protective buffer zones, the development of ecological models, and the effect of elevated CO_2 concentrations on plants and animals. Basic research in these areas is needed now to determine how species might respond to climate change and how best to provide for their protection in the future.
- Conduct a review of ecological research within USGCRP and across Federal agencies. Such a review would evaluate how much ecosystem research relevant to climate change and other long-term ecological problems (e.g., loss of biodiversity) is being done, and would identify important gaps. A review of all research on 'natural resources' has not yet been conducted across the Federal agencies. Existing analyses suggest that a great deal of money is spent on

research relevant to the environment, but how much is useful to understanding long-term ecological problems is not known. Further, there is currently no mechanism for consolidating results from disparate research efforts into "general patterns and principles that advance the science and are useful for environmental decisionmaking. Without such synthesis studies, it will be impossible for ecology to become the predictive science required by current and future environmental problems' (97). An effort to characterize and synthesize ongoing research could help bridge the gap between basic research and natural resource planning. Such a review could be conducted by the Office of Science and Technology Policy, the National Academy of Sciences, or an independent commission.

- Provide funding for the Fish and Wildlife Conservation Act of 1980 (P.L. 96-366). This law establishes a Federal cost-share program for "nongame" species conservation. It has already been enacted, but has never been funded. Many States have prepared initial plans that could qualify for Federal matching funds, making it a target of opportunity to promote natural area conservation at the State level. With some amendments to promote multispecies, or "ecosystem," protection at the State level and adequate funding., the Fish and Wildlife Conservation Act could be used to encourage natural area protection and conservation on State and private lands.
- Use acquisition strategies to enhance protection. Federal land-management agencies should be directed to consider whether all future land acquisitions and exchanges: 1) augment underrepresented ecosystems in the Federal natural area holdings, 2) buffer or connect other preserved land parcels, and 3) provide habitat or services likely to persist over the long term despite anticipated stresses. Setting aside a given amount of land within the modern fragmented landscape does not alone ensure that the ecological features for which it is valued will be preserved. To best conserve species, natural areas should include an array of ecosystems and transition zones between them to allow for the many complex interactions that rely on links between different parts of the landscape. By asking agencies to incorporate such concerns into future acquisitions, Congress could minimize future geographic fragmentation and use limited monies to maximize the range of protected ecosystems.

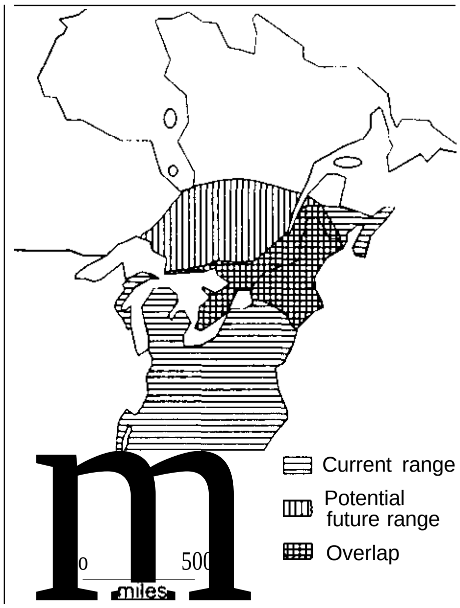
Forests

Forests cover roughly one-third of the U.S. land area, shaping much of the natural environment and providing the basis for a substantial forest-products industry. These forests are enormously variable, ranging from the sparse scrub of the arid interior West to the lush forests of the coastal Pacific Northwest and the South. The Nation's forests provide essential fish and wildlife habitat, livestock forage, watershed protection, attractive vistas, and an array of recreational opportunities. Timber is one of the Nation's most important agricultural crops.

Climate change may pose a significant threat to forests, particularly forests that are not actively managed for timber production. Within a century, climate change might shift the ideal range for some North American forest species more than 300 miles to the north (see fig. 1-7). Such a shift would almost certainly exceed the ability of natural forests to migrate (35, 36, 146). Forests stranded outside their ideal climatic range could suffer from declining growth and increased mortality from climate-related stresses such as insects, disease, and fires (2, 58, 100, 157). Some forests may collapse, and species and unique populations may be lost from isolated ranges if climate change is too rapid.

The most vulnerable forest resources are those in regions subject to increased moisture stress, as

Figure 1-7-Current and Projected Range of Beech Under Climate Change



NOTE: Based on climate projections from the Goddard Institute for Space Studies GCM under the assumption of a doubling of atmospheric CO_2. To convert miles to kilometers, multiply by 1.609.

SOURCE: Office of Technology Assessment, 1993, adapted from M.B. Davies and C. Zabinski, "Changes in Geographical Range Resulting from Greenhouse Warming: Effects on Biodiversity in Forests," in: Global Warming and Biological Diversity, R.L. Peters and T.E. Lovejoy (eds.) (New Haven, CT: Yale University Press, 1992).

in the dry continental interiors (14, 15, 159, 191). Forests in coastal regions may be at risk from rising sea levels, with the threat of flooding and saltwater intrusion, or from increases in damaging wind storms (61, 106). Forests with small or highly fragmented ranges may be lost, such as those at the upper elevations of mountains with nowhere to migrate (89). Forests in locations already subject to droughts, fire, and wind damage will be at high risk if the frequency or intensity of these stressors is increased (157).

The extent to which intervention to facilitate adaptation may be practical or desirable is limited. Even timber-industry forests are not intensively managed by the standards of annual agricultural crops. On large areas of public forest lands, even a minimal management response might be viewed as incompatible with the goals for which the forest is held. The challenge is to find unobtrusive and cost-effective means to help ensure that the health and primary services of the Nation's forest resource will not be lost if climate change proves to be as serious a threat to forests as some believe it will be.

The Federal Government can prepare itself to respond to the threats that climate change poses to forests in several ways: 1) by better understanding which forests are at risk (e.g., by supporting research on species sensitivity to climate and monitoring changes in forests); 2) by acting to avoid the potential loss of forest species (e.g., by promoting and improving forest seed banks, mass propagation techniques, and forest-restoration techniques); 3) by being ready to react promptly to the threat of large-scale forest mortality (e.g., by preventing fires, managing pests, or thinning to promote drought tolerance—in forests where such activities are determined to be appropriate); 4) by redirecting incentive programs to encourage improvement in the health of private forests; and 5) by increasing the adaptability of the forest industry and forest-dependent communities to climate change through forest-product research and incentives for diversification.

Given the existing policy levers, the limited money to fund programs, and the poor level of scientific understanding of impacts of climate change on forests, the following subset of policies, discussed in volume 1, chapter 6, are first steps that Congress could take. Each would help the Nation begin to position itself to respond to the effects of climate change on both timber and nontimber forests. These options are justified now either because of existing problems (such as fire, pests, and drought) that will be exacerbated by climate change, or because of the time required to complete the process.

- **Establish an expanded forest seed-bank program.** A rapid climate change could threaten the genetic diversity of U.S. forests. A national effort in the conservation of forest seeds would provide an opportunity to respond to the potential for loss of genetic diversity in the forest resource under climate change. An appropriate goal for such a program would be to maintain sufficient seed variety, or other genetic material, so that much of the original diversity of the Nation's forests could eventually be restored (86, 87). (Current forest seed-collection activities are uncoordinated and focused on only a small number of species (113).) To accomplish this goal., Congress could authorize and fund a National Forest Genetic Resources Program within the Forest Service, providing funds for the construction and operation of seed-storage facilities, for the establishment of associated plantations to be used for continuing seed production, and for a forest genetics research program that would address climate tolerance of trees and means for large-scale propagation. Such a program could be partially supported through fees for private access to the seed collection.

- **Develop strategic plans for responding to major forest declines.** Increased risk of fires and insect damage may result under a warmer climate. The relative value of prevention activities to reduce risk is likely to be increased. The need for aggressive intervention to protect forest resources may also be increased. Because of the need for prompt action and because of the contentiousness that often accompanies forest management, policy rules for pest-control activities and silvicultural management to reduce forest health risks are best established before they are needed. Congress could enact a forest-health bill that would establish criteria that would allow prompt action to protect against threats of catastrophic mortality or restore forests after large-scale mortality and decline. Such a bill might allow for the declaration of temporary forest-health emergencies, under which accelerated actions to protect or restore forest health would be authorized-as long as these actions were consistent with established standards for protection of all forest values. A policy-review group made up of academics, representatives of interest groups, and Federal forestry personnel could develop criteria for undertaking actions to stem forest decline.
- **Prepare for a forest-management response to climate change.** A changing climate may eventually require innovations in forest-management and planting practices. Experimental efforts will be important in establishing a scientific basis for any necessary changes to future management practices that might later be applied to public multiple-use forests. Congress could support a program of research on the Forest Service's Experimental Forests, or other research facilities, to address adaptation to climate change. The Experimental Forests are already designated as outdoor laboratories for evaluating forestry practices. The research could be directed toward finding practical and environmentally appropriate techniques for managing the public forests that will help buffer them or help them adapt to a changing climate.
- **Improve incentives for private management of forest lands.** The Federal Government controls only about one-quarter of the Nation's forestland. In the East especially, where Federal holdings are limited, efforts to support the protection of private forestland may take on increased importance. The Federal Government may use incentives, disincentives, and cooperative approaches to promote the health and productivity of this forestland. Existing subsidy programs under the Cooperative Forestry Assistance Act of 1978 (P.L. 95-313), as amended by the 1990 Farm Bill, provide cost-sharing assistance to owners of small, private forests. Traditional

forest-support programs (e.g., the Forestry Incentives Program) target funds on the basis of potential gains in timber supply. These programs could be modified so that funds could be targeted to areas at high risk of insect and fire damage and to ecologically valuable forestland, which would encourage activities that maintain the health of the private forestland and discourage the further fragmentation of forestland. Expanding the role of the Forest Stewardship and Forest Legacy Programs might help to accomplish these goals. The funding priorities of the Forest Stewardship Program could be clarified, thus ensuring that most funds are targeted to the areas identified above.

CHAPTER 1 REFERENCES

1. Adams, R.M., et aL, "Global climate Change and u s Agriculture," Nature, vol. 345,1990, pp. 219-24.
2. Anderson, R.L., "Effects of Global Climate Change on Tree survival and Forest Peats in the South," paper presented at the Society of American Foresters Convention in Washington, DC, July 30, 1990.
3. Armentano, T. V., R.A. Park, and L.C. Cloonan, "Impacts on Coastal Wetlands Throughout the United States," in: Greenhouse *Effect, Sea Level Rise, and Coastal Wetlands,* EPA 230-05-86-013, J. Titus (cd.) (Washington, DC: U.S. Environmental protection Agency, Office of Policy, Harming and Evaluation, July 1988).
4. Assel, R.A., "Implication of CO_2 Global Warming on Great Lakes Ice coves," *Climatic Change,* vol. 18, 1991, pp. 377-95.
5. Ausubel, J.H., "A Second Look at the Impacts of Climate Change," American Scientist, vol. 79,1991, pp. 210-21.
6. Bazzaz, F.A., and E.D. Fajer, "Plant Life in a CO_2-Rich World," *Scientific American,* VOL 266, No. 1, January 1992, pp. 68-74.
7. Bean, M.J., "Federal Laws and Politics Pertaining to the Maintenance of Biological Diversity on Federal and private Lands, " contractor report prepared for the OH&of Technology Assessment's report *Technologies to Maintain Biological Diversity, Oct.* 1, 1985.
8. Bean, M.J., "Waterfowl and Climate change: A Glimpse into the Twenty-Firat Century," *Orion Nature Quarterly,* spring 1989, pp. 22-27.
9. Bean, M.J., "Non-Indigenous Species *in* the United States: The Role of the united States Department of the Interior in Non-Indigenous Species Issues," contractor paper prepared for the Office of Technology Assessment, November 1991.
10. Beatley, T., "Hurricane Hugo and Shoreline Retreat: Evaluating b Effectiveness of the south Carolina Beachfront Management Act," final report to the National Science Foundation, September 1992.
11. Beatley, T., "Risk Allocation Policy in the Coastal Zone: The current Framework and Future Directions," contractor paper prepared for the Office of Technology Assessment, February 1993.
12. Bernabo, C.J., Science and Policy Associates, Inc., testimony at hearings before the House committee on Science, Space, and Technology, May 19, 1993.
13. Biasing, T.J., and A. Solomon, Response *of the North American Corn Belt to Climatic Warming,* Publication 2134, Environmental Sciences Division (oak Ridge, TN: Oak Ridge National Laboratory, 1982).
14. Botkin, D.B., R.A. Nisbet, and T.E. Reynales, "Effects of climate Change on Forests of the Great Lake States," in: *The Potential Effects of Global Climate Change on the United States, Appendix Deforests,* J.B. Smith and D.A. Tirpak (eds.) (Washington, DC: Us. Environmental Protection Agency, Office of Policy, Planning and Evaluation, 1989).
15. Bowes, M.D., and R.A. Sedjo, "Impacts and Responses to Climate Change in Forests of the MINK Region," *Climatic Change,* vol. 24, June 1993, pp. 63-82.
16. Brickson, B., "The River," *Western* Water, July/August 1990.
17. Brown, G.E., Jr., Chairman, Committee on Science, Space, and Technology, U.S. House of Representatives, "Report of the Task Force on the Health of Researc̈hairman's Report," Serial L, Committee Print, *1992.*
18. California Department of Water Resources, *California Water: Looking w the Future,* Bulletin *16087,* November *1987.*
19. *Carnegie C*ommission *on science,* Technology and Governm@ *Environmental Research and Development: Strengthening the Federal Infrastructure* (Washington, *DC: Carnegie c*ommission on Science, Technology and Government, December 1992).
20, Chite, R.M., Library of Congress, Congressional Research Service, "Federal Crop Insurance: current Issues and Options for Reform, " 92-318 ENR, March 1992.
21. Chite, R.M., Library of Congress, congressional Research Service, "Agricultural Disaster Assistance," IB91099, July 1992,
22. Cline, W.R., The Economics@ Global *Warming* (Washington, *DC: Institute* for International Economics, 1992).
23. Cline, W.R., "The Impact of Global Warming on the United States: A Survey of Recent Literature," contractor paper prepared for the office of Technology Assessment, March 1993.
24. committee on Earth and Environmental Sciences (CEES), Mitigation and Adaptation Research Strategies working Group, *Directory of Federal Research Activities Related* to *Mitigation of or Adaptation to Global Change* (Washington, *DC:* CEES, 1992).
25. committee on Earth and Environmental Sciences (cIIES), *Our* Changing *Planet: The FY 1993 U.S. Global Change Research Program* (Washington, *DC:* CEES, *1992).*
26. Committee *on Earth and Environment*Sciences (CEES), our *Changing Planet: The FY* 1994 *U.S. Global Change Research Program* (Washington, *DC:* CEES, 1993),

27. Committee on Science, Engineer@, and Public Policy, Panel on Policy Implications of Greenhouse Warming, National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base* (Washington, DC: National Academy Press, 1992).

28. Conservation Foundation, *Protecting America's Wetlands: An Action Agenda, the final report* of' the National Wetlands Policy Forum (Washington, DC: Conservation Foundation 1988).

29. Cooper, C.F., "Sensitivities of Western U.S. Ecosystems to climate Change," contractor report prepared for the Office of Technology Assessment, August 1992.

30. Council for Agricultural Science and Technology, *Preparing U.S. Agriculture for Global Climate Change,* Task Force Report No. 119 (Ames, Iowa: Council for Agricultural Science and Technology, 1992).

31. Crumpacker, D., "Status and Trends of Natural Ecosystems in the U.S.," contractor report prepared for the Office of Technology Assessment's report *Technologies to Maintain Biological Diversity, September* 1985.

32. Dahl, T.E., *Wetlands Losses in the United States, 1780s to 1980s, report* to Congress (Washington, DC: U.S. Department of the Interior, Fish and Wildlife Service, 1990).

33. Dahl, T.E., and C-E. Johnson, *Status and Trends of Wetlands in the Conterminous United States, Mid-1970's to Mid-1980's* (Washington, DC: U.S. Department of Interior, U.S. Fish and Wildlife Service, 1991).

34. Davis, G.D., "Natural Diversity for the Future Generations: The Role of Wilderness, ' in: *Proceedings of the Natural Diversity in Forest Ecosystems Workshop,* J.L. Cooley and J.H. Cooley (eds.) (Athens, GA: University of Georgia, 1984).

35. Davis, M.B., ''Lags in Vegetation Response to Greenhouse Warming," *Climatic Change, vol.* 15, 1989, pp. 75-82,

36. Davis M.B., and C. Zabinski, "Changes in Geographical Range from Greenhouse Warming: Effects on Biodiversity in Forests, " in: Global *Warming and Biological Diversity,* R. Peters and T. Lovejoy (eds.) (New Haven, CT: Yale University Press, 1992).

37. de Golia, J., *Everglades: The Story Behind the Scenery (Las* Vegas, NV: KC Publications, Inc., 1978).

38. Dowlatabadi, H., and M.G. Morgan, "Integrated Assessment of climate change," *Science,* vol. 259, Mar. *26, 1993, pp. 1813, 1932.*

39. *Drake,* B. G., "Effect of Elevated CO_2 on Chesapeake Bay Wetlands," *Responses of Vegetation to Carbon Dioxide,* vol. 51, April-November 1990.

40. Duncan, M.R., "U.S. Agriculture: Hard Realities and New Opportunities," *Economic Review: Federal Reserve Bank of Kansas City,* February 1989, pp. 3-20.

41. Easterling, W.E., "Adapting United States Agriculture to climate Change, " contractor report prepared for the Office of Technology Assessment January 1993.

42. Ek, C.W., Library of Congress, Congressional Research Service, "Normal Crop Acreage," 89-467 ENR, August 1989.

43. Emanuel, K.A., "The Dependence of Hurricane Intensity on Climate," *Nature,* vol. *326, 1987,* pp. 483-85.

44. Environmental and Energy Study Institute, *1993 Briefing Book on Environmental and Energy Legislation* (Washington, DC: *Environmental and Energy study* Institute, 1993).

45. Federal Emergency Management Agency, "Projected Impact of Relative Sea Level Rise on the National Flood Insurance Program," October 1991.

46. Frederick, K., "Overview," in: Scarce *Water and Institutional Change, K. Frederick* (ed.)(Washington, *DC:* Resources for the Future, 1986).

47. Gillilan, D., "Innovative Approaches to Water Resource Management," contractor report prepared for the Office of Technology Assessment, September 1992.

48. Glantz, H.M. (cd.), *Societal Responses to Regional Climate Change: Forecasting by Analogy (Boulder, CO:* Westview Press, 1988).

49. Gleick, P., "Vulnerability of Water Systems," in: *Climate Change and U.S. Water Resources (New* York, *NY:* John Wiley & sons, 1990).

50. Godschalk, D., D. Brewer, and T. Beatley, *Catastrophic Coastal Storms: Hazard Mitigation and Development Management* (Durham, *NC: Duke* University Press, 1989).

51. Gore, A., "From Red Tape to Results: Creating a Government that Works Better and Costs Less," report of the National performance Review, Sept. 7, 1993.

52. Gornitz, V., T. White, and R Cushman, "Vulnerabiii'ty of the U.S. to Future Sea Level Rise," in: *Proceedings of the 7th Symposium on Coastal and Ocean Management* (Long Beach, CA American Society of Civil Engineers, 1991).

53. Graham, R.L., M.G. Turner, and V.H. Dale, "How Increasing CO_2 and Climate Change Affect Forests," *Bioscience, vol. 40, No. 8, September* 1990, pp. *575-87.*

54. Gramp, K.M., AH. Teich, and S.D. Nelson, *Federal Funding for Environmental R&D: A Special Report,* R&D Budget and Policy Project, The American Association for the Advancement of Science, AAAS publication number 92-48S (Washington, DC: AAAs, 1992).

55. Halpin, P.N., "Ecosystems at Risk to Potential Climate Change," contractor report prepared for the Office of Technology Assessment, June 1993.

56. Harkness, W.E., H.F. Lins, and W.M. Alley, "Drought in the Delaware River Basin, 1984-85," in: *National Water Summary 1985—Hydrological Events and Surface WaterResources,* U.S. Geological Survey Water Supply Paper 2300 (Washington, DC: U.S. Government Printing Office, 1986).

57. Harper, S, C., L.L. Falk, and E.W. Rankin, *The Northern Forest Lands Study of New England and New York* (Rutland, VT: U.S. Department of Agriculture, Forest Service, and Governors' Task Force on Northern Forest Lands, April 1990; *2nd priming,* February 1992).

58. Hedden, R.L., "Global Climate Change: Implications for Silviculture and Pest Management," in: *Proceedings, Fifth Biennial Southern Silvicultural Research Conference, General Technical Report No. SO-74 (New Orleans, LA:* USDA Forest Service, Southern Forest Experiment Station, 1989).

59. Herrick, C.N., and D. Jamieson, "The Social Construction of Acid Rain: Some Implications for Science/Policy Assessment," paper to be presented at the 18th annual meeting of the Society for the Social Studies of Science, Nov. 19-21, 1993.

60. Hey, D., "Prairie Potholes," in: *Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy,* National Research Council (Washington DC: National Academy Press, 1992), pp. 505-509.

61. Hodges, D.G., et al., ' 'Regional Forest Migrations and potential Economic Effects," *Environmental Toxicology and Chemistry,* vol. 11, 1992, pp. 1129-136.

62. Holdridge, L.R., *Life Zone Ecology (San* Jose, Costa Rica: Tropical Science Center, 1%7).

63. Hubbard, D.E., "Glaciated Prairie Wetland Functions and Values: A Synthesis of the Literature," U.S. *Fish and Wildlife Service Biological Report,* vol. *88, No. 43, 1988.*

64. Hudson, W.E., *Landscape Linkages and Biodiversity* (Washington, *DC:* Defenders of Wildlife and Island Press,1992).

65. Institute of Ecology, *Experimental Ecological Reserves: A Proposed National Network,* report prepared for the National Science Foundation(Washington, DC: U.S. Government Printing Office, June 1977).

66. Intergovernmental Panel on Climate Change, Response Strategies Working Group, Coastal Zone Management Subgroup, *Global Climate Change and the Rising Challenge of the Sea (The Hague: Ministry* of Transport, 1992).

67. Intergovernmental Panel on Climate Change (IPCC), World Meteorological Organiźtion, and United Nations Environment Program, *Climate Change: The IPCC Impacts Assessment, report* prepared for IPCC by Working Group II, W. McG. Tegart, G. Sheldon, and D. Griffith (eds.) (Canberra, Australia: Australian Government Publishing Service, 1990).

68. Intergovernmental Panel on Climate Change (IPCC), World Meteorological Organization, and United Nations Environment Program, *Climate Change: The IPCC Response Strategies, report* prepared for IPCC by Working Group III, 1990.

69. Intergovernmental Panel on Climate Change (IPCC), World Meteorological Organization, and United Nations Environment Program, *Climate Change: The IPCC Scientific Assessment, report* prepared for IPCC by Working Group I, J. Houghton, G. Jenkins, and J. Ephraums (eds.) (Cambridge, England: Cambridge University Press, 1990).

70. Intergovernmental Panel on Climate Change (IPCC), World Meteorological Organization, and United Nations Environment Program, Climate *Change 1992: The Supplementary Report to the IPCC Scientific Assessment,* report prepared for IPCC by Working Group I, J. Houghton, B. Callander, and S. Varney (eds.) (Cambridge, England: Cambridge University Press, 1992).

71. Jacoby, H.D., "Water Quality," in: *Climate Change and U.S. Water Resources,* P.E. Waggoner (cd.) (New York, NY: John Wiley & Sons, 1990).

72. Jarvis, P.G., "Atmospheric Carbon Dioxide and Forests," *Philosophical Transactions of the Royal Society of London,* vol. B *321, 1989,* pp. *369-92.*

73. Jones, E., and W. Stolzenberg, "Building in Coastal Barrier Resource Systems' (Washington DC: National Wildlife Federation, 1990).

74. Kalkstein, L.S., "Impacts of Global Warming on Human Health: Heat Stress Related Mortality," in: *Global Climate Change: Implications, Challenges and Mitigation Measures, S.* Majumdar et al. (eds.) (Philadelphia: Pennsylvania Academy of Sciences, 1992).

75. Kane, S., J. Reilly, and J. Tobey, "An Empirical Study of the Economic Effects of Climate Change on World Agriculture," *Climatic* Change, vol. 21, No. 1, 1992, pp. 17-36.

76. Kareiva, P.M., *Biotic Interactions and Global Change,* J, Kingsolver and R. Huey (eds.) (Sunderland, MA: Sinauer Associates, Inc., 1993).

77. Karl, T.R., "Missing Pieces of the Puzzle," *Research & Exploration,* vol. 9, No. 2, Spring 1993, pp. 23449.

78. Keith, V.F., C. DeAvila, and R.M. Willis., "Effect of Climate Change on Shipping within Lake Superior and Lake Erie," in: *The Potential Effects of Global Climate Change on the United States, EPA-230-05-89-050,* J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1989).

79. Kemezis, *K.,* "Babbitt to Test Ecosystem Policy in the Everglades," *Environment Week,* Feb. 25, 1993.

80. Kennedy, V.S., "Anticipated Effects of Climate Change on Estuarine and Coastal Fisheries," *Fisheries,* vol. 15, No. 6, 1990, pp. 16-25.

81. Kimball, B.A., NJ. Rosenberg, and L.H. Allen, Jr, (eds.), *Impact of Carbon Dioxide, Trace Gases and Climate Change on Global Agriculture, Special* Publication No. 53 (Madison, WI: American Society of Agronomy, 1990).

82. Klarin, P., and M. Hershman, "Response of Coastal Zone Management Programs to Sea Level Rise in the united states," *Coastal Management,* vol. 18, 1990.

83. Kusler, J.A., *Our National Wetlands Heritage: A Protection Guidebook* (Washington, *DC:* Environmental *Law Institute 1983).*

84. Kusler, JA., and M-E. Kentula, *Wetland Creation and Restoradon: The* Status of the Science (Washington DC: Island Press, 1990).

85. Leatherman, S., "Impact of Accelerated Sea Level Rise *on Beaches and Coastal* Wetlands,' in: Global *Climate Change Linkages,* James C. White (cd.) (Amsterdam, The Netherlands: Elsevier Science Publishing, 1989).

86. Ledig, F.T., A *Strategy to Manage Forest Genetic Resources in the United States (Berkeley,* CA: U.S. Department of Agriculture, Forest Service, Institute of Forest Genetics, Pacific Southwest Research Station, 1992).

87. Ledig, F.T., and J.H. Kitzmiller, "Genetic Strategies for Reforestation in the Face of Global Climate Change, " *Forest Ecology and Management,* 1991.

88. Lettenmai"es, D., T. Gan, and D. Dawdy, "Interpretation of Hydrologic Effects of Climate Change in the Sacramento-San Joaquin River Basin, California," in: *The Potential Effects of Global* Climate *Change on the United States, Appendix* A: *Water Resources,* J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1989).

89. Leverenz, J.W., and DJ. Lev, ''Effecta of Carbon Dioxide-Induced Climate Changes on the Natural Ranges of Six Major Commercial Tree species in the western united States,'' in: *The Greenhouse Effect, Climate Change, and U.S. Forests,* W. Shands and J. Hoffman (eds.) (Washington, DC: The Conservation Foundation, 1987), pp. 123.155.
90. Lewandrowski, J., and R. Brazee, ''Government Farm Programs and Climate change: A First Look,'' in: *Economic* Issues *in Global Climate* Change: Agriculture, *Forestry, and Natural Resources,* J. Reilly and M. Anderson (eds.) (Boulder, CO: Westview Press, 1992), pp. 132-147.
91. Light, S., L. Gunderson, and C. Helling, ''The Everglades: Evolution of Management in a Turbulent Ecosystem,'' Arthur c. Marshall Laboratory, university of Florida, Gainesville, unpublished manuscript, 1993.
92. Lilliehoim, R.J., *Preserves at Risk: An Investigation of Resource Management Strategies, Implications, and Opportunities,* contractor report prepared for the Office of Technology Assessment, January 1993.
93. Linder, K-P., and MR. Inglis, ''The Potential Effects of Climate Change on Regional or National Demands for Electricity," in: *The Potential Effects of Global Climate Change on the United States, Appendix H: Infrastructure,* J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1989).
94. Longstreth, J., and J. Wiseman, "The Potential Impacts of climate change on Patterns of Infectious Disease in the united States," in: *The Potential Effects of Global Climate* Change *on the United States, Appendix G: Health,* J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1989).
95. Lovejoy, T.E., "Diverse Considerations," *Biodiversity,* E.O. Wilson (cd.) (Washington, DC: National Academy Press, 1988),
96. Loveland, J.E, and G.Z. Brown, *Impacts of Climate Change on the Energy Performance of Buildings in the United States,* contractor report prepared for the Office of Technology Assessment, December 1990.
97. Lubchenco, J., et al., "The Sustainable Biosphere Initiative: An Ecological Research Agenda,'' *Ecology,* vol. 72, No. 2, 1991, pp. 371-412.
98. Magnuson, J.J., H.A. Regier, and BJ. Shuter, "Potential Responses of Great Lakes Fishes and Their Habitat to Global climate warming," in: *The Potential Effects of Global Climate Change on the United States, Appendix E: Aquatic Resources,* J. Smith and D, Tirpak (eds.) (Washington, DC: Us. Environmental Protection Agency, 1989).
99. Mahlman, J.D., ''Assessing Glottal Climate Change: When Will We Have Better Evidence?" in: *Climate Change and Energy Policy,* Los Alamos *National Laboratory LA-UR-92-502,* L. Rosen and R. Glasser (eds.) (New York, NY: American Institute of Physics, 1992), pp. 17-31.
100. Mattson, WJ., and RA. Haack, "The Role of Drought in Outbreaks of Plant-Eating Insects," *Bioscience,* vol. 37, No. 2, February 1987, pp. 110-18.
101. Mathews, WJ., and E.G. Zimmerman, "potential Effects of Global Warming on Native Fishes of the Southern Great Plains and the Southwest,'' *Fisheries,* vol 15, No. 6,1990, pp. 26-32.
102. McGillivary, D.G., T. Agnew, G.R. Pilkington et al., ''Impacts of Climate Change on the Beaufort Sea-Ice Regime: Implications for the Arctic Petroleum Industry," Canadian Climate Centre Report 92-6 (DownsView, Ontario: Atmospheric Environment Service, 1992).
103. McNeely, J. A., "climate Change and Biological Diversity: Policy Implications," in: *Landscape-Ecological Impact of Climatic Change, M.* Boer and R. de Groot (eds.) (Amsterdam, The Netherlands: 10S Press, 1990), pp. 406-429.
104. McNeely, J.A., "The Future of the National Parks,'' *Environment,* vol. 32, No. 1, 1990, pp. 16-20 and 37-41.
105. Mearns, L., "Implications of Global Warming for Climate Friability and the occurrence of Extreme climate Events," in: *Drought Assessment, Management, and Planning: Theory and Cure Studies,* D. Wilhite (cd.) (Boston, MA: Kluwer Academic Publishers, *1993).*
106. Miller, W.F., P.M. Dougherty, and G.L. Switzer, ''Effect of Rising Carbon Dioxide and Potential Climate Change on Loblolly Pine Distribution, Growth, Survival and Productivity,'' in: *The Greenhouse Effect, Climate Change and U.S. Forests,* W.E. Shands and J.S. Hoffman (eds.) (Washington, DC: The Conservation Foundation 1987).
107. Moreau, D.H., "It Will Be a Long Wait for Proof," paper presented at the Southeast Climate Symposium Changing Climate and Water Resources, Charleston SC, Oct. 27-29, 1992.
108. Murphy, D.D., and S.B. Weiss, "Effects of Climate Change on Biological Diversity m Western North America: Species Losses and Mechanisms,'' in: Global *Warming and Biological Diversity,* R.L. Peters and T. E. Lovejoy (eds.) (New Haven, CT: Yale University Press, 1992), pp. 355-368.
109. National Audubon Society, *Report of the Advisory Panel* on the *Everglades and Endangered Species (New* York, NY: National Audubon Society, 1992),
110, National Committee on Property Insurance, *America's Vanishing Coastlines, October 1988.*
111, National Research Council, *Toward an Understanding of Global Change* (Washington, *DC: National Academy* Press, *1988).*
112. National Research Council, *Managing CoastalErosion* (Washington, DC: National Academy Press, *1990).*
113. National Research Council, Managing Global Genetic *Resources: Forest Trees (Washington DC: National Academy Press,* 1991).
114. National Research Council, *Restoration of Aguatic Ecosystems: Science, Technology, and Public Policy* (Washington, *DC: National Academy Press,* 1992).
115. National Research Council, Science *and the National Parks* (Washington, DC: National Academy Press, 1992).
116. National Research Council, *Water Transfers in the West: Efficiency, Equity,* and the *Environment (Washington DC: National* Academy *Press, 1992).*
117. National Research Council, *Research to Protect, Restore, and Manage the Environment* (Washington, *DC:* National Academy Press, 1993).
118. National Research Council, *Setting Priorities for Land Conservation (Washington DC:* National Academy Press, 1993).

119. Nelson, J.W., "The Duck Depression of the 1980' -An Agenda for Recovery,' a Ducks Unlimited Discussion Paper, Ducks Unlimited, Inc., Long Grove, IL, 1989.
120. Nelson, R.K., "Athapaskan Subsistence Adaptations in Alaska," in: *Alaska Native Cultures in History*, U. Kotani and M. Workman (eds.) (Osaka, Japan: National Museum of Ethnology, 1980).
121. Oechel, W. C., "Effects of Anticipated Changes in Global Climate and Atmospheric CO_2 on Western Ecosystems: Chaparral and Associated Forest Ecosystems," contractor report prepared for the Office of Technology Assessment, July 1992.
122. Oechel, W.C., "Sensitivities of Alaskan Biological and Social Systems to Climate Change: A Scenario," contractor report prepared for the Office of Technology Assessment May 1993.
123. Oechel, W.C., and W.D. Billings, "Effects of Global Change on the Carbon Balance of Arctic Plants and Ecosystems, " in: Arctic *Ecosystems in a Changing Climate: An Ecophysiological Perspective*, F.S. Chapin III, R.L. Jefferies, J.F. Reynolds, G.R. Shaver, and J. Svoboda (eds.) (San Diego, CA: Academic Press, 1992), pp. 139-68.
124. Oechel, W.C., and B.R. Strain, "Native Species Responses to Increased Carbon Dioxide Concentration" in: *Direct Effects of Increasing Carbon Dioxide on Vegetation*, DOE/ER-0238, B. Strain and J. Cure (eds.) (Washington DC: U.S. Department of Energy, December 1985).
125. Oechel, W.C., et al., "Recent Changes of Arctic Tundra Ecosystems from a Net Carbon Dioxide Sink to a Source," *Nature*, vol. 361, 1993, pp. 520-23.
126. Oversight Review Board of the National Acid Precipitation Assessment Program (NAPAP), *The Experience and Legacy of NAPAP: Report to the Joint Chairs Council of the Interagency Task Force on Acid Deposition* (Washington, *DC: NAPAP*, April 1991).
127. Park, R.A., et al., "The Effects of Sea Level Rise on U.S. Coastal Wetlands,' in: *The Potential Effects of Global Climate Change in the U. S., Appendix B: Sea Level Rise*, J. Smith and D. Tirpak (eds.) (Washington DC: U.S. Environmental Protection Agency, 1989).
128. Parker, B.B., National Oceanic and Atmospheric Administration (NOAA), Ocean and Lake Levels Division, Office of Ocean and Earth Sciences, National Ocean Service, NOAA, "The Use of Long Historical Sea Level Records in the Study of Climate and Global Change, ' paper presented at Marine Technology Society '92, Washington, DC, Oct. 19-21, 1992.
129. Parry, M.L., and P.N. Duinker, ''Agriculture and Forestry, " in: *Climate Change: The IPCC Impacts Assessment*, W. McG. Tegart, G. Sheldon, and D. Griffiths (eds.), WMO/UNEP Intergovernmental Panel on Climate Change (Canberra, Australia: Australian Government Publishing Service, 1990).
130. Peine, J., J. Burde, and W. Hamrit, "Threats to the National Wilderness Preservation System," in: *Wilderness Benchmark 1988: Proceedings of the National Wilderness Colloquium, General* Technical Report SE-51 (Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, 1989), pp. 133-141.
131. Peters, R.L., "The Effect of Global Climatic Change on Natural Communities," in: *Biodiversity*, E.O. Wilson (cd.) (Washington, DC: National Academy Press, 1988), pp. 450-464.
132. Peters, R.L., and J.D. Darling, "The Greenhouse Effect and Nature Reserves," *Bioscience*, vol. 35, 1985, p. 707.
133. Peters, R.L., and T.E. Lovejoy (eds.), *Global Warming and Biological Diversity (New* Haven, *CT: Yale* University Press, 1992),
134, Poiani, K.A., and W.C. Johnson, "Global Warming and Prairie Wetlands: Potential Consequences for Waterfowl Habitat," *Bioscience, vol. 41, No.* 9, October 1991, pp. 611-18;
135. President's Commission *on Americans Outdoors, Amen"cans Outdoors: The Legacy, The Challenge* (Washington, DC: Island Press, 1987).
136. Property Claim Services, A Division of American Insurance Services Group, Inc., "Hurricane Andrew's Estimated *Cost to Property Insurers* Revised to $15.5 Billion by Property Claim Services," February 1993 (press release).
137. Rawson, J.M., Library of Congress, Congressional Research Service, "New Crops and New Farm Products: A Briefing," 88-771 ENR, December 1988.
138. Rawson, J.M., Library of Congress, Congressional Research Service, "Agricultural Research and Extension: Current Issues," 93-83 ENR, January 1993.
139. Ray, G.C., M.G. McCormick-Ray, and F.M. potter, "Global Climate Change and the Coastal Zone: Evacuation of Impacts on Marine Fisheries and Biodiversity of the U.S.," contractor report prepared for the Office of Technology Assessment, February 1993.
140. Ray, G.C., et al., "Effects of Global Warming on the Biodiversity of Coastal-Marine Zones," in: *Global Warming and Biological Diversity*, RL. Peters and T.E. Lovejoy (eds.) (New Haven, CT: Yale University Press, 1992), pp. 91-104.
141. Reisner, M., *Cadillac Desert: The American West and Its Disappearing Water (New* York, *NY:* Viking Penguin, Inc., 1986).
142. Riebsame, W., and J. Jacobs, "Climate Change and Water Resources in the Sacramento-San Joaquin Region of California," working paper 64, Natural Hazards Research and Applications Information Center, University of Colorado, *December* 1988.
143. Riebsame, W., S. Changnon, and T. Karl, *Drought and Natural Resources Management in the United States: Impacts and Implications of the 1987-89 Drought* (Boulder, CO: Westview Press, 1991).
144. Rind, D., R Goldberg, J. Hansen, C. Rosenzweig, and R. Ruedy, "Potential Evapotranspiration and the Likelihood of Future Drought," *Journal of Geophysical Research, vol. 95, No. 7*, 1990, pp. 9983-10004.
145. Ritchie, J.T., B.D. Baer, and T.Y. Chou, "Effect of Global Climate Change on Agriculture m the Great Lakes Region," in: *The Potential Effects of Global Climate Change on the United States, Appendix C, Volume 1: Agriculture, J. Smith* and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1989), pp. 1-1 to 1-30.
146. Roberts, L. "HowFastCanTrees Migrate?" Science, Feb. 10, 1989.

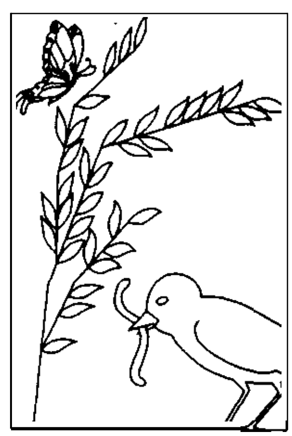
147. Rocky Mountain Institute, *Water Efficiency: A Resource for Utility Managers, Community Planners, and Other Decision-makers, in* cooperation with the U.S. Environmental protection Agency Office of Water (Snowmass, CO: Rocky Mountain Institute, 1991).
148. Rosenberg, NJ., "Adaptation of Agriculture to Climate Change," *Climatic Change,* vol. 21, No. 4,1992, pp. 385-405.
149. Rosenzweig, C., "Potential Effects of Climate Change on Agricultural Production in the Great Plains: A Simulation Study," in: *The Potential Effects of Global* Climate *Change on the United States, Appendix C, Volume I: Agriculture,* J. *Smith and* D, Tirpak (eds.) (Washington, DC: U.S. Environmental protection Agency, 1989), pp. 3-1 to *3-43.*
150. Rosenzweig, C., and M. Parry, Climate Change *and World Food Supply* (Oxford, England: University of Oxford, in press).
151. Ruttan, V.W., "W. Parry: Climate Change and World Agriculture," *Environment,* vol. *33, 1991,* pp. 25-29 (book review).
152. Scott, M.J., B. Csuti, and S. Caicco, "Gap Analysis: Assessing Protection Needs," in: *Landscape Linkages and Biodiversity* (Washington, DC: Island Press, 1991), pp. 15-26.
153. Sheer, D., "Reservoir and Water Resources Systems in the Face of Global Climate Change," contractor report prepared for the office of Technology Assessment, December 1992.
154. Simberloff, D., J.A. Farr, J. Cox, and D.W. Mehlman, "Movement Corridors: Conservation Bargains or Poor Investments?" *Conservation Biology,* vol. *6, No. 4,* 1992, pp. 493-504.
155. Smith, J.B., "Amending Natural Resource Statutes to Anticipate Climate Change," contractor report prepared for the Office Of Technology Assessment, -1993.
156. Smith, J.B., and J, Mueller-Vollmer, "Setting Priorities for Adapting to Climate Change," contractor report prepared for the Office of Technology Assessment, February 1993.
157. Smith, W.H., "United States Forest Response and Vulnerability to Climate Change," contractor report prepared for the Office of Technology Assessment, May 1992.
158. Solley, W., R Pierce, and H. Perlman, *Estimated Use of Water in the United States in 1990,* United States Geological Survey (USGS) Survey Circulail081 (Washington, DC: USGS, 1993).
159. Solomon, A.M., "Transient Response of Forests to CO_2-Induced Climate Change: Simulation Modeling Experiments in Eastern North America," *Oecologia,* vol. *68, 1986,* pp. 567-79.
160. Swanson, GA., and H.F. Duebbert, "Wetland Habitats of Waterfowl in the Prairie Pothole Region," in: *Northern Prairie Wetlands,* A. vander Valk (cd.) (Ames, IA: Iowa State University Press, 1989), pp. 228-67.
161. Titus, J.G. (cd.), *Greenhouse Effect, Sea Level Rise, and Coastal Wetlands,* EPA 230-05-86-013 (Washington, DC: Us. Environmental Protection Agency, Office of Policy, Planning and Evaluation, July 1988).
162. Titus, J.G. "Greenhouse Effect and Coastal Wetland Policy: How Americana Could Abandon an Area the Size of Massachusetts at Minimum Cost," *Environmental Management,* vol. 15, No. 1, 1991, pp. 39-58.
163. Titus, J.G., and M. Greene. "An Overview of the Nationwide Impacts of Sea Level Rise," in: *The Potential Effects of Global Climate Change on the United States, Appendix B: Sea Level Rise,* J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1989).
164. Turner, M, D. Swezy, and J. Longstreth, "Potential Impacts of Global Climate Change in the U. S.: Importation/ Exacerbation of Human Infectious Diseases," contractor report prepared for the Office of Technology Assessment, December 1992.
165. United Nations, *United Nations Convention on Climate Change,* Article *2 and* Article *4, Sec. 2(b),* 1992.
166. Us. Advisory Commission on Intergovernmental Relationa (ACIR), *Coordinating Water Resources in the Federal System: The Groundwater-Surface Water Connection* (Washington, *DC:* ACIR, October 1991).
167. U.S. Army Corps Engineers, Institute for Water Resources, "IWR Review Report for U.S. Congress, Office of Technol-Ogy Assessment, in Reference to Draft Report on Systems at Risk from Climate Change," IWR Policy Study 93-PS-1, July 1993.
168. U.S. Congress, General Accounting Office (GAO), National *Wildlife Refuges: Continuing Problems with Incompatible Uses Call for Bold Action,*GAO/RCED-89-196 (Washington, *DC:* U.S. GAO, September 1989).
169. Us. Congress, General Accounting Office (GAO), *Wetlands Overview: Federal and State Policies, Legislation, and Programs,* GAO/RCED-92-79FS (Washington, *DC:* U.S. GAO, November 1991).
170. Us. congress, office of Technology Assessment, *Wetlands: Their Use and Regulation,* OTA-0-206 (Washington, DC: U.S. Government Printing office, March *1984).*
171. U.S. Congress, Office of Technology Assessment, *Technologies to Maintain Biological Diversity,* OTA-F-30 (Washington, *DC:* Us. Government Priming Office, March 1987).
172. U.S. Congress, Office of Technology Assessment, *Changing by Degrees: Steps to Reduce Greenhouse Gases,* OTA-O-482 (Washington, DC: Us. Government Printing office, February 1991).
173, Us. Congress, office of Technology Assessment, *Energy Efficiency in the Federal Government: Government by Good role?* OTA-E-492 (Washington, DC: U.S. Government Printing Office, May 1991).
174. Us. congress, Office of Technology Assessment, *A New Technological Era for Amen-can Agriculture,* OTA-F-474 (Washington, *DC:* Us. Government Printing Office, August 1992).
175. U.S. Congress, Office of Technology Assessment, *Harmful Non-Indigenous Species in the United States* (Washington, *DC: Government Printing* Office, *in* press).
176. U.S. Department of Agriculture, Forest Service, *Blue Mountains Forest Health Report: New Perspective in Forest Health* (Portland, OR: U.S. Forest Service, Pacific Northwest Region, April 1991).

177. U.S. Department of Energy, Argonne National Laboratory, Environmental Assessment and Information Sciences Division, Technology and Environmental Policy Section, *Effects of Scientific Uncertainties on the Accuracy of Global Climate Change Predictions: A Survey of Recent Literature, DOE! internal* report, M.E. Fernau and D.W. South (eds.) (Argonne, IL: U.S. Department of Energy, October 1991).
178. U.S. Department of Energy, Office of Energy Research, Office of Basic Energy Sciences, Carbon Dioxide Research Division, *Direct Effects of Increasing Carbon Dioxide on Vegetation,* DOE/ER-0238, B. Strain and J. Cure (eds.) (Washington DC: U.S. Department of Energy, December 1985).
179. U.S. Department of the Interior, *The Impact of Federal Programs, Volume 1: The Lower Mississippi Alluvial Plan and the Prairie Pothole Region,* a report to Congress by the Secretary of the Interior, October 1988,
180. U.S. Department of the Interior, Bureau of Land Management, *Fish and Wildlife 2000: Special Status Fishes Habitat Management,* BLM/SC/PT - 91/005+6844 (Washington, *DC:* U.S. Government Printing Office, May 1991).
181. U.S. Department of the Interior, Bureau of Land Management, *Fish and Wildlife 2000: Annual Report of Accomplishments FY 1991 (Washington* DC: U.S. Government Printing Office, 1991).
182. U.S. Department of the Interior, Fish and Wildlife Service, *An Overview of Major Wetland Functions and Values,* FWS/OBS-84/18, contractor paper prepared by J. Sather and R. Smith (Washington DC: U.S. Fish and Wildlife Service, September 1984).
183. U.S. Department of the Interior, Fish and Wildlife Service, *Endangered and Threatened Species Recovery Program* (Washington, DC: U.S. Government Printing Office, December 1990).
184. U.S. Department of the Interior, Fish and Wildlife Service, *Wetlands: Meeting the President's Challenge—1990 Wetlands Action Plan* (Washington, *DC:* U.S. Fish and Wildlife Service, 1990).
185. U.S. Department of the Interior, Fish and Wildlife Service, *Refuges* 2003-A *Plan for the Future of the National Wildlife Refuge System, Issue 2, March* 1991.
186. U.S. Department of the Interior, Fish and Wildlife Service, and U.S. Department of Commerce, Bureau of the Census, 1991 *National* Survey *of Fishing, Hunting, and Wildlife-Associated Recreation* (Washington, DC: U.S. Government Printing Office, 1993).
187. U.S. Department of the Interior, National Park Service, *The National Parks: Shaping the System (Washington DC:* National Park Service, 1991).
188. U.S. Environmental Protection Agency, *The Potential Effects of Global Climate Change on the United States, EPA-23@05-89-050,* J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, December 1989),
189. U.S. Geological Survey, "Coastal Hazards," in: *National Atlas of the United States of America* (Reston, VA: U.S. Geological Survey, 1985) (map).
190, U.S. House of Representatives, Reclamation Projects Authorization and Adjustment Act of 1992-Conference Report, Report 102-1016 (Title XXXIV: Central Valley Project Improvement Act; Title XXX: Western Water Policy Review), Oct. 5, 1992.
191. Urban, D.L., and H.H. Shugart, "Forest Response to Climatic Change: A Simulation Study for Southeastern Forests," in: *The Potential Effects of Global Climate Change on the United States, Appendix D: Forests,* J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, *1989).*
192, Van Sickle-Burkett, V., et al., National Wetlands Research Center, U.S. Fish and Wildlife Service, tables describing coastal wetland vulnerabilities to climate change, prepared for U.S. Office of Technology Assessment, May 1992.
193. Wahl, R., "The Management of Water Resources in the Western U.S. and Potential Climate Change," contractor report prepared for the Office of Technology Assessment October 1992.
194. Warren, R. S., Coastal Wetland *Vulnerabilities to Climate Change,* contractor paper prepared for the Office of Technology Assessment, July 1992.
195. Washington, W., "Reliability of the Models: Their Match with Observations," in: Climate *Change and Energy Policy,* L. Rosen and R. Glasses (eds.) (New York: American Institute of Physics, 1992).
1%. Webb, T., "Past Changes in Vegetation and Climate: Lessons for the Future," in: Global *Warming and Biological Diversity,* R. Peters and T. Lovejoy (eds.) (New Haven, CT: Yale University Press, 1992), pp. 59-75.
197. Wilhite, D., "Drought Management and Climate Change," contractor report prepared for the Office of Technology Assessment, December 1992.
198, Willard, D.E., et al., "Wetland Vulnerabilities to Climate Change," contractor paper prepared for the Office of Technology Assessment, August 1992.
199. Willard, D.E., and LD. Kosmond, *A Watershed-Ecosystem Approach to Lund and Water Use Planning and Management,* contractor report prepared for the Office of Technology Assessment, Aug. 28, 1992.
200. Wingerd, D., and M. Tseng, "Flood and Drought Functions of the U.S. Army Corps of Engineers," in: *National Water Summary 1988-89—Hydrologic Events and Floods and Droughts,* U.S. Geological Survey Water-Supply Paper 2375 (Washington, DC: U.S. Government Printing Office, 1991).
201. World Resources Institute (WR.I), The World Conservation Union (IUCN), and United Nations Environment Programme (UNEP), *Global Biodiversity* Strategy: Policy-Makers' Guide (Baltimore, MD: WRI Publications, 1992).
202. Wright, G.R., *Wildlife Research and Management in the National Parks (Chicago, IL:* University of Illinois Press, 1992).

A Primer on Climate Change and Natural Resources 2

This chapter summarizes the current state of knowledge about climate change and describes the interaction of climate variables with natural systems. Background information key to understanding the impacts described in each of the resource chapters (coasts, water, agriculture, wetlands, preserves, and forests) is included here. This chapter illustrates the range of effects climate change could cause across systems and at different spatial and temporal scales.

Human activities have increased the rate at which greenhouse gases--carbon dioxide (CO_2) methane (CH_4, nitrous oxide (N_2O), and chlorofluorocarbons (CFCs--are building up in the atmosphere. This increase is likely to lead to changes in climate that could have significant effects on natural systems. The first-order effects of a buildup of greenhouse gases-increasing average temperature, rising sea level, and changes in precipitation and evapotranspiration--can be estimated with some confidence at the global scale. Global average temperature may increase about 2 OF (1 ‘C) by 2030 and sea level is predicted to rise by about 8 inches (20 centimeters)[1] in the same period; precipitation and evapotranspiration globally will also increase.



As scientists consider smaller spatial scales, their certainty about these effects decreases. Some midcontinent regions are likely to become warmer and drier rather than warmer and wetter, for example, but not enough is known yet about climate change on a regional scale to be confident about the direction and magnitude of changes. A decade or more of research will be needed before such precision is available. Second- and third-order effects, such as changes in individual plants and animals or whole ecosystems, are utimately the impacts that humans care

[1] To convert inches to centimeters (cm), multiply by 2.540,To

about. These changes in the natural and managed systems that societies depend on have socioeconomic consequences and result in costs or benefits.

Plants and animals are more immediately affected by extreme events, such as droughts, floods, or storms, than they are by changes in the long-term averages of climate variables. However, individuals may not be able to tolerate sustained changes in average temperature and precipitation. Such conditions might, for example, lead to increased vulnerability to pests, disease, and fires. Repeated stress will adversely affect not only individuals but also populations and species, potentially resulting in altered ecosystem ranges and composition.

As the climate changes and average temperature increases, the extremes experienced by ecosystems will change as well. The hottest temperatures may be hotter than previously experienced; the coldest temperatures may not be as cold as they are now. Ultimately, temperature shifts may alter the geographic range of species and ecosystems. Climate change may also benefit some plants and animals. Certain plants, for example, may derive benefits from the rising concentration of CO_2 in the atmosphere, which can act like a fertilizer. Higher temperatures could enable some plants and animals to increase their geographic ranges.

Ecosystems are always changing and would continue to do so without climate change. However, projected rates of change in temperature exceed the estimated rates for the past 15,000 years, which averaged about 2°F(1°C) per 1,000 years; under a changing climate, temperatures could rise 3 to 8 OF (1.5 to 4.5 °C) over the next century. These changes may be too rapid to allow forest ecosystems to migrate with the changing climate. Atmospheric concentrations of CO_2 are changing 30 to 100 times faster than shown in ice-core records, which go back millennia. Natural ecosystems are more vulnerable to climate change than are managed ones, such as farms and plantation forests, because active measures--


U.S. FISH AND WILDLIFE SERVICE

Many animals, such as this Rocky Mountain coyote, require large expanses of remote and undisturbed habitat to sustain populations. Human disturbance or fragmentation of habitat leads to declines in prey populations and vegetation cover. Affected species can migrate, decline, or alter their food sources.

irrigation, replanting, and fertilizing, for example are much more difficult to undertake in natural areas.

Many natural systems are already degraded by pollution and geographic fragmentation. Additional human-caused stress may lead to undesirable changes in the values and functions of natural systems from which humans now benefit. 'Uner stress, natural systems of plants and animals tend to breakup and reformulate in new systems with different species or mixes of species" (21). The total change in an ecosystem depends not only on its sensitivity to climate change, but also on the system's absolute sensitivity to a variety of other changes that influence soil and water chemistry or habitat fragmentation (21).

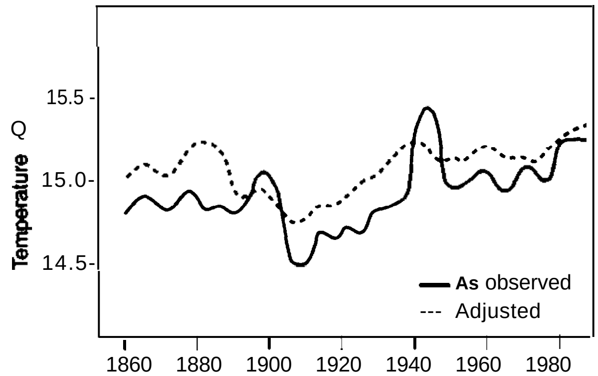
HOW DO WE KNOW CLIMATE IS CHANGING?

The Earth's average temperature has increased 0.8 OF (0.45 'C) over the past 100 years, with an uncertainty range of +/-0.27 °F (+/-0.15 °C). The broad range reflects many inaccuracies introduced in the 100-year land-based temperature record by recording temperatures in cities (which tend to be warmer than rural areas),[2] using different instruments over time, and inadequate and changing spatial coverage.

Because the climate system is so inherently variable, it takes a long time to detect trends. Besides greenhouse gases, urban ozone, decreases in stratospheric ozone, increases in acidic air pollution, volcanic aerosols, and the solar cycle are all likely to have influenced the observed global temperature record. For example, the sum of all known greenhouse gases emitted to the atmosphere to date should have increased the heat-trapping capacity of the atmosphere by 2.1 watts per square meter (W/m*). However, over the past few decades, other forces could have counteracted as much as 50 percent of the effect by cooling the earth. Urban air pollution (e.g., soot and acid aerosols) could have offset the warming by up to 24 percent, ozone depletion by CFCS, 10 percent, and increased cloudiness by 20 percent. Although these cooling effects temporarily mute the greenhouse effect, they do not negate it, so net warming is expected. Simultaneously, solar irradiance (the output of the sun) may have enhanced the greenhouse effect by 14 percent.

Other naturally occurring events can confound the temperature record, too, such as the 3- to 7-year occurrences of El Niño. Volcanic eruptions (such as El Chichon in 1982 and Mount Pinatubo in 1991) can more than offset the entire greenhouse effect temporarily (for 2 to 4 years).[3] Recent satellite temperature measurements taken over a 12-year period show no warming trend (84). This satellite record cannot be used to refute global Warming for three reasons: 1) the record of measurements is over too short a period; 2) two major volcanic eruptions occurred during that period (Chichon and Pinatubo), followed by a several-year cooling due to the particles they injected into the atmosphere; and 3) the satellite does not measure the near-surface temperature of the earth; rather, it integrates a 6,500-yard (6,000-meter) swath of the atmosphere (48).

Figure 2-l—Long-Term Global Temperature Record



NOTE: Global average temperature from raw observations (solid line) vs. data adjusted for known biases (dashed line). Lack of data quality and contlnuity has led to an undesirable level of uncertainty about these records. To convert °C to °F, multiply by 1.8 and add 32.

SOURCE: T.R. Karl, 'Missing Pieces of the Puzzle," in: Research and *Exploration,* Spring 1993, pp. 235-49.

Despite all the confounding factors, the long-term temperature record shows warming that is consistent with that calculated by the general circulation models (GCMS) (44) (see fig. 2-1 and box 2-A). The observed 0.8 OF rise is within—but at the low range of--the 0.7 to 2.0 OF (0.4 to 1.1 °C) that models predict. The warming is not "statistically significant' '-that is, it is not outside the range of normal variability. The unequivocal detection of a climate change signal from such complicated records requires at least another decade of measurements (44). The nine warmest years since 1891 were all in the 1980s and early 1990s (6). Several ancillary pieces of evidence consistent with warming, such as a decrease in Northern Hemisphere snow cover, a simultaneous

2 Bias due to "the heat island effect' is likely to be less than 0.1 °F (0.05 'C), or less than 10 percent of the observed temperature increase (43).

3 For example, Pinatubo injected 25 million tons (23 billion kg) of sulfur dioxide 15 miles (25 km) into the stratosphere; the cooling caused by reflectivity of those particles should offset the warming from greenhouse gases for 2 years until the particles settle out of the atmosphere.

Box 2-A–What the Models Tell Us: GCMs and Others

To describe how the climate system operates and to predict how changes in the composition of the atmosphere will affect climate, scientists have developed models known as general *circulation models* (GCMs). GCMs are composed of mathematical equations that describe the physical climate processes and interrelationships, including seasonal changes in sunlight, global air currents, evaporation and condensation of water vapor, and absorption of heat by t he oceans. The models incorporate basic physical principles (such as the conservation of energy and mass) and empirical evidence from observations of how the climate system seems cooperate (such as statistical equations describing t he humidity and temperature at which clouds generally form). The four major GCMs have generated somewhat different predictions about how climate might change largely because they use different empirical evidence and starting assumptions and incorporate different sets of climate variables. Even models that agree on global averages may predict different regional distrbutions because they have different ways of accounting for small-scale climate processes.

The differences in climate change predictions from the various major climate models have drawn considerable attention. So, too, has the fact that observed changes in global average temperature have been lower than initial estimates. Many models have predicted that based on the increases of human-generated greenhouse gas emissions (particularity carbon dioxide (CO_2) emitted during fossil fuel combustion) over the past century, global temperatures should already have increased by 0.5 to 2.0 ‘F (0.3 to 1.0 °C). Measurements of warming to date suggest that global average surface-air temperatures have increased approximately 0.5 to 1.0‘F (0.3 to 0.6 °C)--on the low end of the predicted range (45).[1]

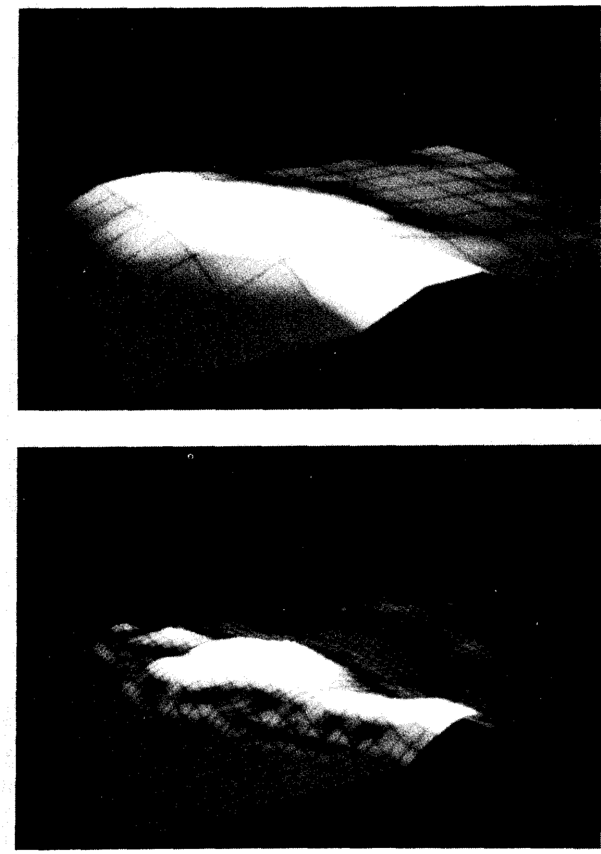
That global warming appears to be proceeding more slowly than predicted maybe due to difficulties in distinguishing short-term climate patterns from long-term trends, as well as to the complex and incompletely characterized interactions, of oceans, clouds, and air pollution with weather and climate (44, 92). Natural variations in weather (e.g., rainfall and temperature) occur over years or decades, which may mask longer-term (century and millennium) climate patterns for many years (63). In addition, oceans have an enormous capacity to absorb heat which may delay atmospheric warming for some time (81, 66). Clouds also play an important but uncertain role in moderating planetary climate. Depending on their composition and location, clouds may either cool the planet by reflecting incoming solar radiation or warm it by contributing to the greenhouse effect so it is not clear whether, in the aggregate, they contribute to or somewhat offset global warming (1, 66). Finally, global warming may be offset somewhat in the Northern Hemisphere because some human-generated pollution (particularly sulfur aerosols) may actually exert a cooling effect: when converted to sulfate particles in the atmosphere, they reflect incoming solar radiation (44, 66).

Generalities and uncertainties

GCMs paint the following general picture of global climate change. Average global air temperatures will increase. With increased temperatures will come an increase in average global precipitation because warmer air causes faster evaporation, speeding up the rate at which water vapor becomes available for aloud formation and precipitation. Increased temperatures will cause the water in oceans to expand (water expands as it warms above 39 OF (4 °C)), and as ocean volume increases, sea levels will rise. Sea level rise may be moderated if increased

[1] Global-average temperature statistics are compiled from historical temperature measurements from weather stations around the world. Accurate interpretation of historical temperature data Is complicated and controversial because changes in measurement techniques and locations over the past century make the data difficult to compare. Data analysis is further complicated by the urban “heat island effect”—local warming in areas with many buildings and paved surfaces that tend to trap heat-which has raised temperatures at some monitoring stations, reflecting changes in local climate apart from any potential global changes. The estimated temperature change reported here was a consensus figure developed by the Intergovernmental Panel on Climate Change (IPCC) that attempts to account for both the changes In measurement and the confounding effects of data from urban areas.

temperature and water-holding capacity of the air lead to more snow at the poles, which may cause arctic ice sheets to grow thicker in the near future; on the other hand, warmer temperatures could cause parts of the Greenland and Antarctic ice sheets to melt, causing even more sea level rise. Beyond these generalities, significant uncertainties remain about regional impacts, rates of change, and feedbacks. Regional predictions are quite murky, and they are the ones that are most important to individual resources and human societies. A variety of factors, including local or mesoscale effects of hills, and vegetation boundaries, are important in determining regional climate. GCMs cannot at present incorporate features this small (see the figure in this box) because spacing between grid points is between 150 and 800 miles (250 and 1,000 kilometers)[2] (94). Because models differ in how they treat these physical features and because the current generation of models is only beginning to incorporate the modeling of ocean currents and aloud cover, it is not surprising that the major GCMs differ markedly in predicting regional changes in precipitation, soil moisture, and other hydrologic variables. For example, certain models predict that precipitation will increase in some regions white others suggest that it will decrease (83). The range (and therefore uncertainty) in model output for soil moisture and runoff is even greater than it is for precipitation (49).



NOTE: Models cannot yet incorporate regional features adequately because grid sizes are too large. The smaller the grid size, the more complex and time-consuming each model run becomes. The top figure shows how a 480-km grid can obscure important geologic features. The bottom figure shows what the topography of the United States looks like with a 120-km model grid. The degree of resolution in the bottom figure is typical of present global weather prediction models.

SOURCE: National Center for Atmospheric Research.

Most climate modelers agree that precipitation is most likely to increase at high latitudes and that the water-holding capacity of the atmosphere (cloudiness) will be largest in low to midlatitudes (30). In the midcontinent areas, especially in summer, evapotranspiration may outstrip precipitation, and thus soil moisture and runoff would decrease. The potential for more-intense or longer-lasting droughts would therefore increase. Some scientists (78) suggest that GCMs (because of their lack of realistic land-surface models) understate the potential for the intensification of summertime drought in low to midlatitudes. If current trends in greenhouse gas emissions continue, they predict the frequency of severe drought in the United States would be expected to increase dramatically, with effects becoming apparent sometime on the 1990s (78).

A second likely regional consequence of global warming is that it will lead to changes in the type and timing of runoff. Snowmelt is an important, source of runoff in most mountainous areas. Warmer temperatures in such

2 To convert miles tokilometers, multiply by 1.609.

(Continued on next page)

Box 2-A–What the Models Tell Us: GCMs and Others-(Continued)

areas would cause a larger proportion of winter precipitation that now falls as snow to fall as rain. Thus, the proportion of winter precipitation stored in mountain snowpack would decrease. Winter runoff would increase, and spring runoff would correspondingly decrease. During times when flooding could be a problem, seasonal changes of this sort could have a significant impact on water supplies because adequate room in reservoirs would have to be maintained (53), and thus some early runoff would probably have to be released.[3]

Uncertainty surrounds predictions of the rate at which climate change may proceed. Most assessments of climate change have assumed that it will proceed gradually and continuously until the climate reaches some new equilibrium (21). These assessments attempt to characterize what the climate might eventually be like when the equivalent of doubled $C0_2$ has been reached; relatively few studies have examined the intermediate, or transient climate stages. However, a few suggest that the change may not linear and gradual. For example,the capacity of the oceans to absorb heat may delay warming for sometime, but there maybe some threshold after which ocean heat absorption slows and a relatively rapid warming of air temperatures follows (81)-or proceeds in steps in a series of punctuated equilibria (relatively rapid change for a short time followed by a period of relative stability), so transient climate stages might be important (15).

Uncertainties also arise from lack of knowledge about potential climate feedbacks--that is, processes that occur in response to global warming that either augment or diminish the effect in complex and interacting ways. For example, at warmer temperatures, the atmosphere can hold more water vapor, which is a powerful greenhouse gas, and this will magnify warming. On the other hand, some portion of the additional water vapor could form into clouds, which can, depending on their size, shape, and distance from the Earth's surface, reflect solar radiation and either amplify or offset some of the warming. The role of ice and snow in climate systems has not yet been quantified, and it is not clear whether it will prove to be an additional feedback. Warming in the polar regions will likely melt some portion of the polar ice caps, reducing the extent of land and ocean covered by them. Ice and snow are more reflective than either land or water; reducing the amount of ice and snow will allow both land and sea to absorb more heat= In addition, sea ice tends to insulate the ocean; when the ice is not present the ocean may release heat to the atmosphere more readily. Both processes could add to the warming cycle, so that as the atmosphere becomes warmer, it triggers various additional processes that will make it warmer still (66).

Other feedbacks may, however, counteract warming. For example, some scientists point out that vegetation may grow better in an atmosphere with higher concentrations of $C0_2$ Increased plant growth could allow plants to take up more carbon from the atmosphere, potentially acting as a brake to greenhouse warming (61).

Despite the uncertainties attached to climate change predictions, there are many areas of agreement on the global, and even some regional, outlines of change. The effects on ecosystems and natural resources are more uncertain. Even if models could now generate accurate regional and local climate predictions, scientists do not yet have the theoretical knowledge to predict with confidence how ecosystems will react to the predicted climate changes—and how ecosystem response will translate into impacts on natural resources and on the people who depend on them. And they are further still from being able to forecast how or whether systems could adapt

3 The California Department of Water Resources has estimated, for example, that if average temperatures warm by5'F (3 'C), winter snowmelt runoff would increase, but the average April-July runoff would be reduced by about 30percent (M. Roos, Chief Hydrologist, California Department of Water Resources, personal communication, 1992).

SOURCES: Intergovernmental Panei on Climate Change (lPCC), World Meteorological Organization, and United Nations Environment Program, C//mate *Change:* The *IPCC Scientific Assessment,* report prepared for IPCC by Working Group 1, J.T. Houghton, G.J. Jenkins, and J.J. Ephraums (eds.) (Cambridge, England: Cambridge University Press, 1990); Intergovernmental Panel on Climate Change, World Meteorological Organization, and United Nations Environment Program, *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment,* report prepared for IPCC by Working Group i, J.T. Houghton, B.A. Callander, and S.K. Vamey (eds.) (Cambridge, England: Cambridge University Press, 1992); U.S. Congress, Office of Technology Assessment (OTA), *Changing by* Degrees: *Steps* to *Reduce Greenhouse Gases,* OTA-O-42 (Washington, DC: U.S. Government Printing Office, February 1991).

decrease in Arctic sea ice, continued melting of alpine glaciers, and a rise of sea level (48), have also been corroborated.

WHAT CAUSES CLIMATE CHANGE?[4]

The Earth's atmosphere is a natural greenhouse. Sunlight passes through the atmosphere and strikes the Earth, and as the planet warms and radiates heat, a large share of the heat is trapped by gases in the atmosphere, primarily CO_2 and water vapor. Although these gases make up only 0.25 percent of the atmosphere by volume, they are responsible for increasing the average temperature of the Earth from O OF (the temperature it would be without these natural greenhouse gases) to 59 oF. The evolution of such an atmosphere offered the appropriate conditions for the development of life on Earth. Humans have added more CO_2 and other greenhouse gases (CH_4, N_2O, and CFCS) to the atmosphere over the past 100 years. These gases effectively trap the heat that would normally be radiated from the earth into space. Instead, heat is reflected back to the Earth, and both the surface and the lower atmosphere get warmer-causing global warming. This greenhouse effect is illustrated in fig. 2-2.

An international panel of scientists was established in 1988 to assess potential climate change and its impacts. This Intergovernmental Panel on Climate Change (IPCC) includes more than 50 countries, and operates under the aegis of the World Meteorological Organization and the United Nations Environment Program. IPCC issued a report in 1990 and an update in 1992 (44, 45) that represent the best scientific assessment to date about climate change and its causes. IPCC scientists agree on the basic atmospheric mechanisms that make the planet a greenhouse. They also concur that human activities, such as burning fossil fuel, deforestation, and agriculture, have increased the rate at which greenhouse gases are emitted to the atmosphere, and that the concentrations of those gases in the atmosphere are increasing.

WHAT CHANGES IN CLIMATE ARE PREDICTED?[5]

Carbon Dioxide and Other Greenhouse Gases

In contrast to measurements of temperature and precipitation, which do not reveal clear trends, measurements of greenhouse gases show significant, steady increases over the past century.[6] For example, the concentration of atmospheric CO_2, the most important greenhouse gas (other than water vapor), has been systematically monitored since 1958 at the Mauna Loa Observatory in Hawaii.[7] It has been increasing steadily for the past 35 years. Data from air bubbles in ice cores show that preindustrial atmospheric CO_2 concentrations were 280 parts per million (ppm); in 1990, the concentration had increased by more than 25 percent to an annual average of 353 ppm and is increasing at 0.5 percent per year (see fig. 2-3, lower data points). Seventy to 90 percent of the CO_2 added to the atmosphere today (about 8

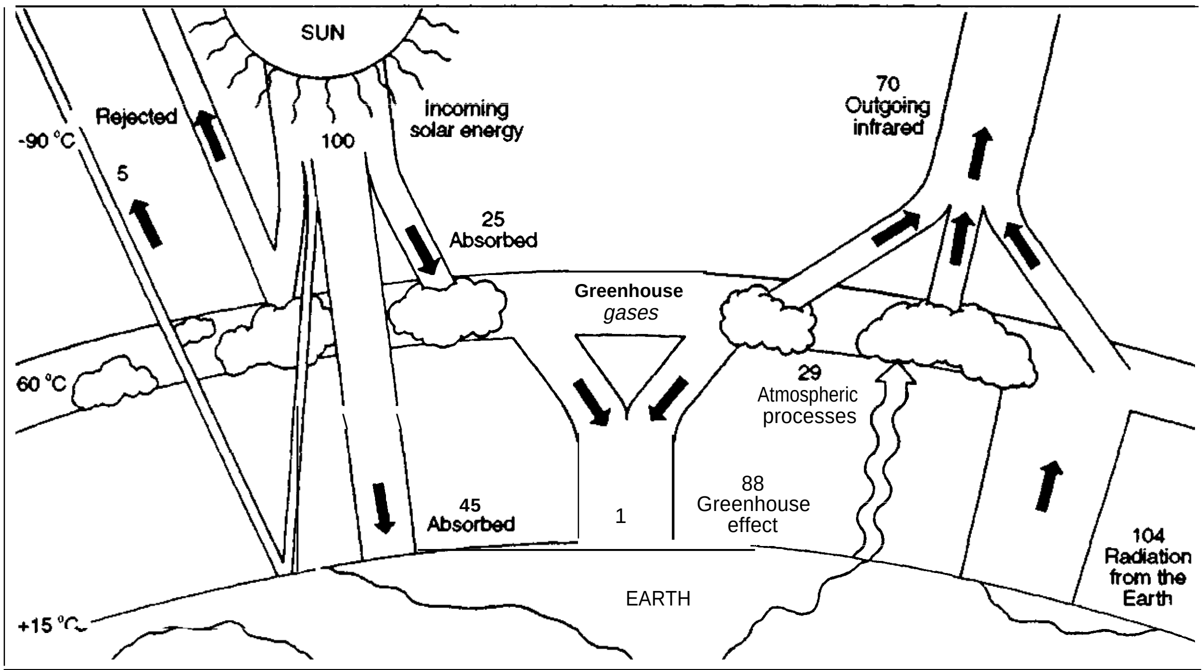
[4] This section briefly summarizes the mechanisms and the greenhouse gases that contribute to the greenhouse effect. For a more detailed treatment of climate change, see chapter 2 of OTA'S previous report on climate change, *Changing by Degrees* (88). That report also examines how the United States and other countries could reduce emissions that contribute to climate change.

[5] The predictions given throughout this section are based on an equivalent doubling by 2025 to 2050 of greenhouse gas concentrations from preindustrial levels. In addition, the predictions refer to a future *equilibrium climate*—that is, one in which the climate has finished changing and the climate system has arrived at a new balance—rather than the *transient climate*, or intermediate stage, that occurs as climate change is underway. Scientists debate whether the climate will reach anew equilibrium or whether we are instead entering an era of continuous change. Equilibrium may not be reached for centuries. (J. Mahlman, Director, Geophysical Fluid Dynamics Laboratory, Princeton University, July 28, 1993, at a briefing sponsored by the World Resources Institute and the National Oceanic and Atmospheric Administration.)

[6] For a more detailed discussion of the emissions and effects of greenhouse gases, see reference 88.

[7] CO_2 is responsible for about 70 percent of the radiative forcing (heat trapping) caused by greenhouse gases in the 1980s.

Figure 2-2—The Greenhouse Effect



NOTE: Radiation flows are expressed here as a percent of total incoming or outgoing energy. Incomlng solar radiation is partially reflected back into space (30 percent) and partially absorbed by the atmosphere, ice, oceans, land, and biomass of the Earth (70 percent).The Earth then emits *radiant energy back* into space. The "greenhouse effect" refers to the trapping of some of the radiant ● nqy the Earth emits by atmosphere gains, both natural and anthropogenic. As a result of this effect, the Earth's surface and lower atmosphere warm.

SOURCE: U.S. Congress, Office of Technology Assessment, *Changing by Degrees: Steps to Reduce Greenhouse Gases, OTA-O-482* (Washington, DC: Government Printing Office, February 1991).

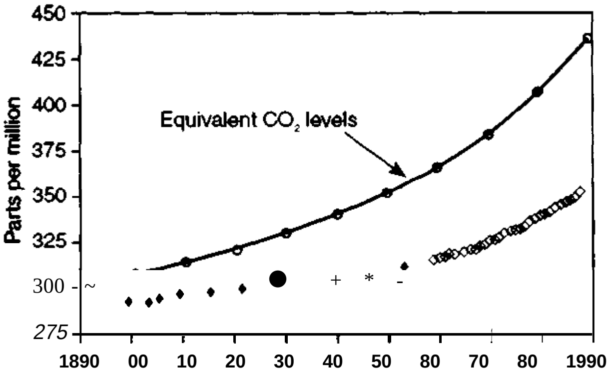
to 9 billion tons, or 7 or 8 trillion kilograms, of carbon each year) is due to the burning of fossil fuels--coal, oil, and natural gas; the remainder is attributed to deforestation. IPCC notes that under a "business-as-usual" scenario, the concentration of $C0_2$ could rise as high as 800 ppm-nearly triple the preindustrial level—by the end of the next century (44). If world emissions were frozen at 1990 levels, CO_2 concentrations would still rise to 400 ppm by about 2070 (see fig. 2-4),[8] and temperatures would continue to rise about 0.4 OF (0.2 'C) per decade for many decades.

Increases in the atmospheric concentrations of the greenhouse gases CH_4, N_2O, and CFCS have also been documented and can be linked to anthropogenic emissions. As the upper line in figure 2-3 shows, these gases effectively augment the greenhouse effect caused by CO_2. Sources of CH_4 emissions include rice paddies, domestic animals (cattle and sheep), natural gas production and delivery, coal production, and landfills (44). CH_4 concentrations increased about 1 percent per year between 1978 and 1987 (from 150 to 168 parts per billion (ppb)). Recently, this increase has slowed to 0.5 percent per year; the cause of this slowdown is unknown (45).

Atmospheric concentrations of N_20 began a rapid ascent in the 1940s and increased at 0.2 to 0.3 percent per year during the mid-1980s, with current concentrations at about 310 ppb. Ice-core

[8] Given that developing countries currently use one-tenth the energy of the developed world and their usage is increasing 6 to 10 percent per year, this later scenario is unrealistic (88).

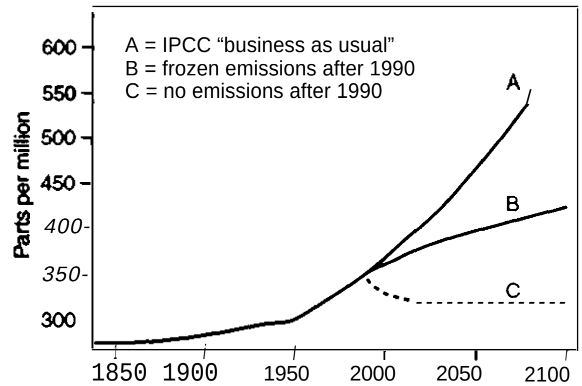
Figure 2-3-Measured and Equivalent CO_2 Concentrations in the Atmosphere



NOTE: The lower points represent atmospheric concentrations of CO_2 from Antarctic ice-core data (1890 to 1950, shown as diamonds) and from recent Mauna Loa observations (1 958 to 1990, shown as stacked squares). "Equivalent CO_2 levels" are shown by the connected circles; this is the additional effect caused by various trace gases (methane, nitrous oxide, and chlorofluorocarbons) expressed In CO_2 equivalents.

SOURCE: R.C, Balling, 'The Global Temperature Data," In: Research & *Exploration, vol.* 9, No. 2, Spring 1993, p. 203.

Figure 2-4-Expected CO_2 Concentrations in the Atmosphere According to Various Emissions Scenarios



SOURCE: M. Heimann, "Modeling the Global Carbon Cycle," paper presented at the First Demetra Meeting on Climate Variability and Global Change, Chiandiano Therme, Italy, Oct. 28-NOV. 3, 1991.

data show preindustrial concentrations of 285 ppb, which had been relatively stable for 2,000 years. Anthropogenic sources appear to be responsible for about 30 percent of N_20 emissions[9]—prirnarily from nylon production, nitric acid production, and the use of nitrogenous fertilizers.[10]

CFCS are humanmade chemicals used primarily for refrigeration and insulation. A worldwide treaty (the Montreal Protocol signed in 1987 and augmented by several subsequent amendments) will eliminate use of these chemicals by the end of the century. The concentration of CFCS in the atmosphere had been increasing at 4 percent per year in the 1980s. These chemicals cause ozone depletion worldwide and the Antarctic ozone hole. Given world action to phase out CFCS, the ozone hole is expected to close in 70 years. CFCS are greenhouse gases and trap heat, but because they also destroy ozone (another greenhouse gas), the net warming from CFCS is approximately zero (45).

Temperature

IPCC predicted that global average temperature would increase at a rate of 0.5 'F (0.3 'C) per decade, amounting to a 5.4 OF (3.0 'C) increase by 2100. Box 2-B summarizes the IPCC findings. Although the global average temperature has increased about 0.80 OF (0.45 'C) over the past 100 years, a warming of 1.4 to 4.0 OF (0.8 to 2.2 °C) is expected as an eventual result of the greenhouse gas concentration increases of the past century (this estimate does not include any warming from future emissions).

[9] J. Mahlman, Director, Geophysical Fluid Dynamics Laboratory, Princeton University, personal communication Aug. 27, 1993.

10 However, the sum of all known anthropogenic and natural sources is still insufficient to explain rates of atmospheric increase (45).

Box 2-B–Highlights of the IPCC Scientific Assessment of Climate Change

IPCC is certain that:

- There is a natural greenhouse effect that already keeps the Earth warmer than it would otherwise be.
- Emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases.

IPCC calculates with confidence that:

- Atmospheric concentrations of the long-lived gases (carbon dioxide, nitrous oxide, and the chlorofluorocarbons) adjust slowly to changes in emissions. Continued emissions of these gases at present rates, would cause increased concentrations for centuries ahead.
- The long-lived gases would require immediate reductions in emissions from human activities of over 60 percent to stabilize their concentrations at today's levels; methane would require a 15 to 20 percent reduction.
- The longer emissions continue to increase at present day rates, the greater reductions would have to be for concentrations of greenhouse gases to stabilize at a given level.

Based on current model results, IPCC predicts that:

- Under the IPCC "business-as-usual" scenario,[1] the global mean temperature will increase about 0.5°F(0.3°C) per decade (with an uncertainty range of 0.4 to 0.9 °F per decade), reaching about 2°F (1 'C) above the present value by 2025 and 5 OF (3 'C) before the end of the 21st century.
- Land surfaces will warm more rapidly than the ocean, and high northern Iatitudes will warm more than the global mean in winter.
- Global mean sea level will rise about 2 inches (6 cm) per decade over the next century, rising about 8 inches (20 cm) by 2030 and 25 inches (65 cm) by the end of the 21st century.

All predictions are subject to many uncertainties with regard to the timing, magnitude, and regional patterns of climate change, due to incomplete understanding of:

- sources and sinks of greenhouse gases,
- clouds,
- oceans, and
- polar ice sheets.

The IPCC judgment is that:

- Global sea level has increased 4 to 8 inches (10 to 20 cm) over the past 100 years.
- Global mean surface air temperature has increased by about 0.80 OF (0.45°C) (with an uncertainty range of 0.5 to 1.0 °F (0.3 to 0.6 'C) over the past 100 years), with the five globally averaged warmest years occurring in the 1980s.
- The size of this warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability. Thus, the observed temperature increase could be largely due to natural variability y; alternatively, this variability and other human factors (such as aerosol air pollution) could have offset a still larger human-induced greenhouse warming. The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more.

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[1] This scenario assumes that few steps are taken to reduce greenhouse gas emissions. The atmospheric concentration of CO_2 would double (over preindustrial levels) by about 2060, but the effective CO_2 concentration (the cumulative effect of all trace gases) would double by about 2030.

SOURCES: Intergovernmental Panel on Climate Change (IPCC), Climate Change: *The Scientific Assessment* World Meteorological Organization and U.N. Environmental Program (Cambridge, England: Cambridge University Press, 1990); Intergovernmental Panel on Climate Change (IPCC), *1992 IPCC Supplement*, World Meteorological Organization and United Nationa Environment Program (Cambridge, England: Cambridge University Press, 1992).

Greenhouse gas concentrations in the atmosphere will have effectively doubled[11] relative to their preindustrial values by 2030 (44, 45). Changes in global temperature will affect global patterns of air circulation and wind, possibly changing the frequency or pattern of convective storms. Some research suggests that a warmer sea surface may lead to a longer cyclone season with more-intense storms. To date, however, evidence on whether storm frequencies will change is inconclusive (81).

On the regional level, average temperatures are expected to increase more in the higher latitudes (in the Arctic and Antarctic), particularly in late fall and winter. In the northeastern part of North America under a doubled CO_2 climate, for example, warming could reach 14OF(8‘C) during the winter (44), and average annual temperatures could increase as much as 18 OF (10 ‘C) in some high-latitude areas (81). In addition, summer warming in the middle latitudes, including much of the United States, could be greater than the global average, potentially reaching 7 to 9 °F (4 to 5 ‘C) in the Great Lakes area (45). In the tropics, however, temperature increases are likely to be less than the global average, and will vary less from season to season. Figure 2-5 (top) shows changes in the average annual, winter, and summer temperature ranges predicted for different regions of the United States used for studies performed for the Environrnental Protection Agency (EPA) (94). Regional temperature predictions such as these are accompanied by only a medium level of confidence, but the predictions are likely to improve within the next decade (8 1).

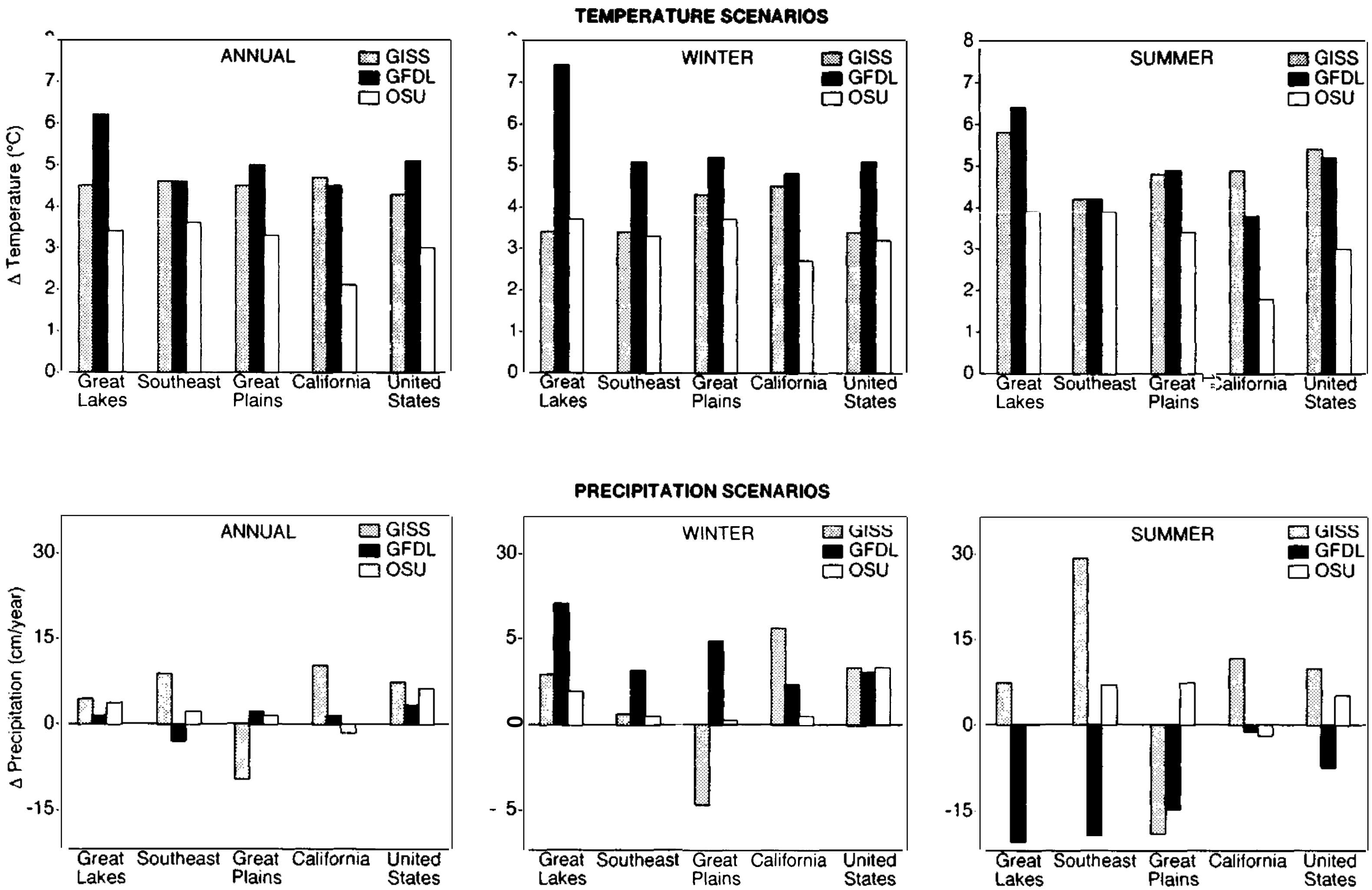
■ Precipitation

Worldwide, average precipitation is expected to increase by 7 to 15 percent under a doubled CO_2 atmosphere. Regional changes will be much more variable, with estimated increases of 20 to 40 percent in some locations (e.g., coasts), and decreases of up to 20 percent in other areas (78, 94). The seasonal distribution and form of precipitation are likely to change. In regions where precipitation increases, a significant share of the increase may come during the winter; in some locations, more winter precipitation will come in the form of rain than snow (81). Although researchers are fairly confident about the predicted rise in average global precipitation, they are much less confident about regional precipitation because of the many uncertainties surrounding small-scale climatic processes. Figure 2-5 (bottom) shows EPA's predicted average annual, winter, and summer precipitation patterns for different regions of the United States (94).

Natural climate variability is great relative to the expected changes in climate variables. Hence, separating the signal of climate change from the noise of natural variability is difficult. One statistical analysis of climate data from the southeastern United States indicates that if average rainfall increased 10 percent, there would be only a 7 percent chance of detecting that trend after 25 years; even a 20 percent increase in rainfall could only be detected with a 65 percent probability after 50 years (63). More concretely, it is difficult to know whether the recent 6-year drought in the western United States is a rare but possible outcome of natural climate variability, an early indication of climate change, or a return to the average climate after a long particularly wet spell. Longer climate records are needed to distinguish among these various possibilities. It is unlikely that researchers will be able to resolve the uncertainties to develop better predictions for another decade or two (81).

[11] The equivalent doubling of CO_2 refers to the point at which the combined total of CO_2 and other greenhouse gases, such as CH_4, built up in the atmosphere have "a radiative effect equivalent to doubling the preindustrial value of carbon dioxide from about 280 ppm to 560 ppm" (81). The full warming associated with that amount of greenhouse gases may be delayed by ocean warming: "The large heat capacity of the oceans will delay realizati"on of full equilibrium warming by perhaps many decades. This implies that any specific time when wc reach an equivalent CO_2 doubling . . . the actual global temperature increase may be considerably less [than 2 to 5°C]. However, this 'unrealized warming' will eventually occur when the climate system's thermal response catches up to the greenhouse-gas forcing.'

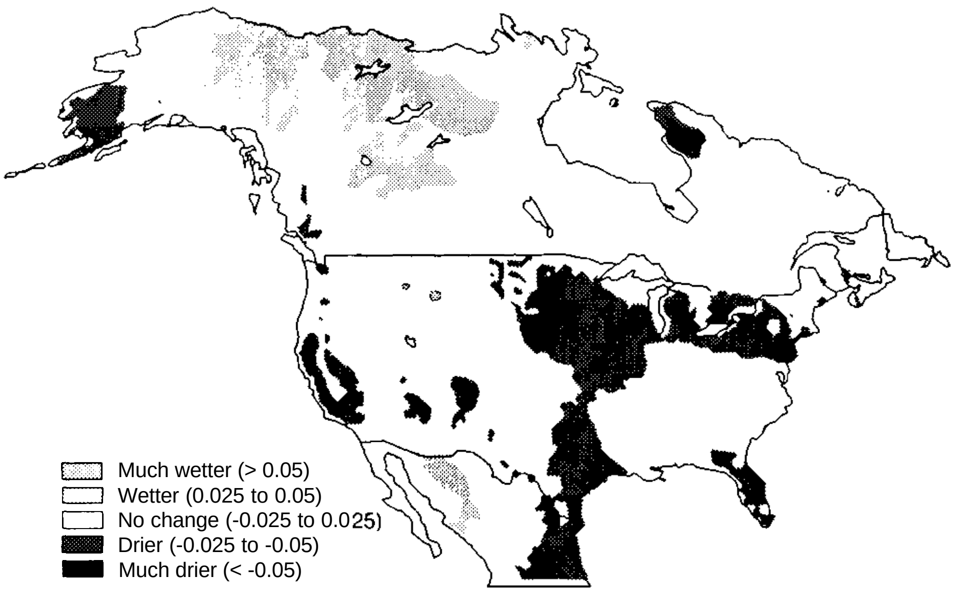
Figure 2-5—GCM-Estimated Changes in Temperature and Precipitation from a Doubling of CO_2



NOTE: GISS=Goddard Institute for Space Studies; GFDL=Geophysical Fluid Dynamics Laboratory; OSU=Oregon State University. To convert °C change to °F, multiply by 1.8; to convert centimeters to inches, multiply by 0.394.

SOURCE: U.S. Environmental Protection Agency (EPA), *The Potential Effects of Climate Change on the United States*, EPA-230-05-89-050, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. EPA, 1989).

Figure 2-6-Potential Soil-Moisture Changes Under the GISS Climate Change Scenario



NOTE: Numbers represent the degree of drying or wetting, calculated as the change in the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET). This ratio is an index of plant-moisture stress, indicating moisture availability relative to moisture demand. GISS-Goddard Institute for Space Studies.

SOURCE: P.N. Halpin, "Ecosystems at Risk to Potential Climate Change," contractor report prepared for the office of Technology Assessment, June 1993.

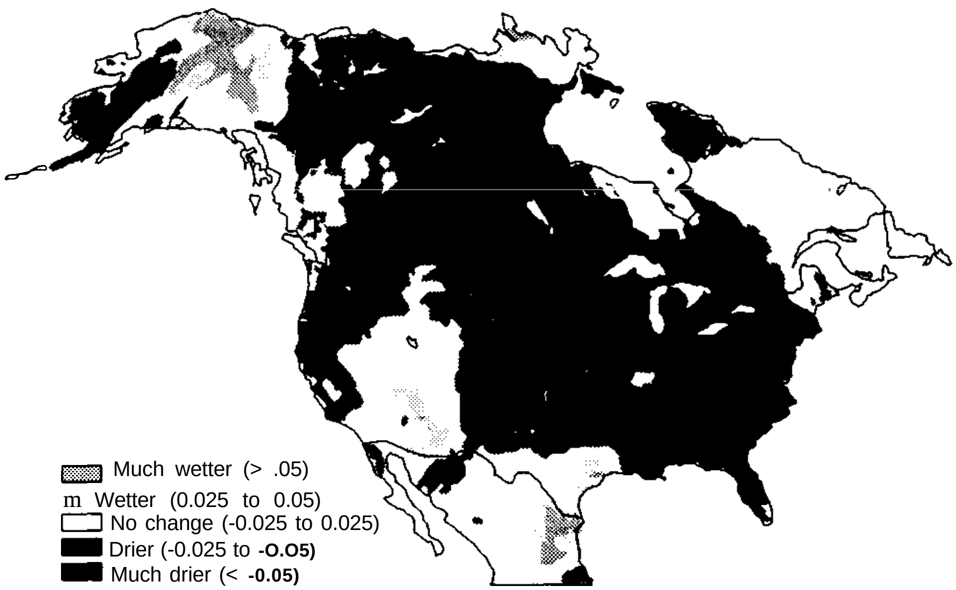
Moisture

Despite overall increases in precipitation, soil *moisture* is predicted to decrease in many mid-continental regions. Soil moisture, which is generally more important for vegetation than is total precipitation, may decrease for two reasons. First, the rate at which moisture evaporates from the soil surface and from plants (evapotranspiration) would increase as temperatures rise. The increased evaporation rates may cause soil to lose moisture at a faster rate than is supplied by the increased precipitation, particularly during the summer. Second, the manner in which added precipitation arrives can affect soil moisture by changing runoff patterns. There are limits to how much soils can absorb at once.[12] For example, sandy soils allow for relatively quick percolation of water through the soil column and into surface- and groundwater systems. However, the percolation rates of clay soils are slow. If increased precipitation comes in a few large storms rather than being evenly distributed over the year, more of it may run off rather than remain in the soil. Thus, increases in average annual precipitation will not necessarily lead to increases in soil moisture and could be accompanied by drier conditions.

Figures 2-6 and 2-7 identify areas of the United States that may face significant changes in soil moisture based on the climate changes projected

12 The ability of soils to retain water varies considerably according to soil composition (the proportion of sand and clay the soil contains) and organic-matter content. In general, sandy soils with little organic material, such as those in central Florida, have a low capacity for water storage. Soils with more clay and a higher organic content, characteristic of the Midwest, can generally retain more water (13).

Figure 2-7—Potential Soil-Moisture Changes Under the GFDL Climate Change Scenario



NOTE: Numbers represent the degree of drying or wetting, calculatad as the change in the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET). GFDL-Geophysical Fluid Dynamics Laboratory.

SOURCE: P.N. Halpin, "Ecosystams at Risk to Potential Climate Change," contractor report prepared for the Office of Technology Assessment, June 1993.

by two GCMS. An index. of soil moisture was calculated as the ratio of available moisture to potential moisture demand (calculated as the ratio of actual evapotranspiration to potential evapotranspiration) .13 White areas in the maps indicate regions of no significant change in the moisture index, dark shading indicates areas of drying, and lighter shading shows areas that become relatively wetter. The Goddard Institute of Space Studies (GISS) scenario (fig. 2-6) produces a mixed result, with large areas of moderate drying intermixed with patches of wetting in the Southeast and northern Rocky Mountain States. The Geophysical Fluid Dynamics Laboratory (GFDL) scenario (fig. 2-7) provides the most extreme outcome for North America, with significant drying across the eastern and central United States and along the Pacific Coast.

Sea Level

IPCC predicts that global average sea levels will rise by around 2 inches (6 cm) per decade for the next century, in contrast to the historic rate of 0.4 inches (1 cm) per decade that occurred since the end of the 19th century. By 2030, IPCC predicts that sea levels will have risen by around 8 inches (20 cm), with a total rise of 26 inches (65 cm) expected by the end of the century (44).

Sea level rise will result from the expansion that occurs as water warms. Oceans will also be

13 Calculated for the Office of Technology Assessment by P. N. Halpin (34). *Evapotranspiration is the* loss of water from the land surface resulting from both evaporation and plant transpiration. Potential *evapotranspiration is the* amount of water that would be lost if there were never a shortage of soil moisture. *Actual evapotranspiration is the actual* amount of water released to the atmosphere (reflecting precipitation and limited availability of soil moisture).

affected by the melting of ice in polar regions. The area of sea ice and seasonal snow cover will also diminish (42). It is likely that ice on the margins will melt more quickly in warmer waters. This result could change the mix of fresh and saline waters in high-latitude seas, and could further change ocean circulation patterns.

Sea level may increase more along some coasts and less along others because sea level rise depends not only on whether the oceans are rising but also on whether adjacent land masses are rising or sinking. Some coasts are sinking as soils are compressed; others are rising due to tectonic forces or as they gradually rebound from the weight of glacial ice that burdened them during the last ice age.[14] Mississippi River Delta in the Gulf of Mexico is subsiding, leading to relatively rapid rates of land loss, while much of the West and the Alaskan coasts are experiencing tectonic uplift and glacial rebound. Thus, the relative sea level rise and the associated land loss is predicted to be greater along the Gulf Coast (as well as in parts of Florida's Atlantic Coast and the South Atlantic States) than along the Pacific Coast. The interaction of sea level rise, altered waves and currents, and storms could lead to greatly increased erosion on sandy coasts and barrier islands (77; see vol. 1, ch. 4).

HOW WILL CLIMATE CHANGE AFFECT NATURAL RESOURCES?

Climate interacts with ecosystems at every level, from the individual to the landscape, throughout the energy and nutrient cycles, and on time scales ranging from seconds to centuries. The effect of climate can be direct, through the action of temperature, evapotranspiration, and sunlight, and indirect, through variables such as wind, cloud cover, ocean currents, and the chemical composition of the atmosphere. For example, photosynthesis rates are affected by the amount of sunlight striking a plant's leaves, which is determined by cloud cover, which in turn is determined by such climatic factors as temperature, evaporation, and wind. Similarly, global temperature affects the amount of precipitation and runoff, which in turn affects the transport of nutrients on land and through wetlands; ocean currents, which are also strongly affected by global temperatures, carry nutrients through marine systems. Indeed, over the long term, climate both shapes the physical landscape and determines where various ecosystems can exist (see fig. 2-8). Climate change of the predicted magnitude is not unprecedented, but scientists who warn of the potential harms of human-induced climate change point out that past global warming and cooling occurred over centuries and millennia rather than decades (see fig. 2-9).[15]

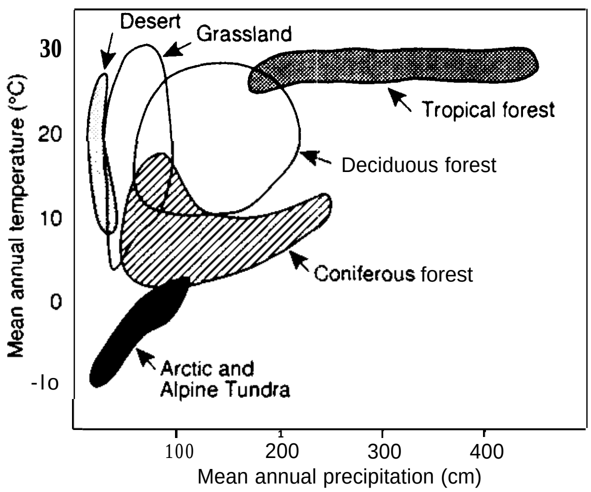
■ Direct Climate Impacts

Climate is often defined as the long-term "average weather.' Likewise, predictions for climate change characterize changes in the Earth's average annual temperature. However, individual plants and animals respond to events on small temporal and spatial scales. Variability is usually more important than annual totals or averages. The seasonal distribution of precipitation and temperature, the form precipitation takes (whether rain or snow), extreme events such as droughts or floods, climate-generated fire cycles, late spring frosts, and early fall freezes are all significant factors in determiningg the survival and productiv-

14 Land in delta areas often subsides. Sediment from upland areas loosely packs layers at the river delta where the river meets the ocean; as sediment accumulates over time, it gradually grows heavier and compresses the underlying layers, so the delta land mass sinks relative to the ocean. Coastal land may also subside in areas where offshore oil and gas extraction or pumping of water from coastal aquifers, has hollowed out underground spaces that are gradually compacted by the masses of land and water above. Much of the northern part of the North American continent is still slowly rising as it rebounds from the weight of glaciers that covered it during the last ice age and is situated on a tectonic plate that is being lifted as the adjacent plate slides beneath it; both processes may cause sea levels on the western and Alaskan coasts to appear lower relative to the coastal land mass.

15 Although recent ice-cover analysis suggests that climate may have shifted several degrees in a decade or less over regions of Greenland.

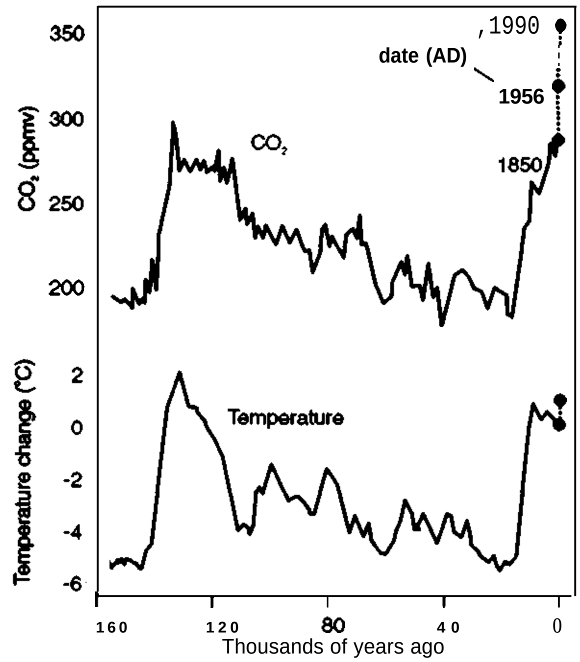
Figure 2-8--Approximate Distribution of the Major Biotic Regions



NOTE: Based on mean annual temperature and mean annual precipitation. To convert °C to °F, multiply by 1.8 and add 32; to convert centimeters to inches, multiply by 0.394.

SOURCE: Adapted from A.L. Hammond, "Ecosystem Analysis: Biome Approach to Environmental Science," Science, vol. 175, 1972, pp. 46-48.

Figure 2-9-Long-Term Temperature and CO_2 Records from Antarctic Ice Cores and Recent Atmospheric Measurements



NOTE: Data show that CO_2 is increasing in the atmosphere much faster than it has at any time over the past 160,000 years. The observed increase in temperature is not yet outside the range of natural variability. To convert °C to °F, multiply by 1.8 and add 32.

SOURCE: C. Lorius, J. Jouzel, D, Raynaud, J. Hansen, and H. Le Trout, "The ice-Core Record: Climate Sensitivity and Future Greenhouse Warming," Nature vol. 347, 1990, pp. 139-145.

ity of individual organisms. One or several extreme events (such as a hurricane or drought) may shape ecosystem boundaries more than many years of "average" weather. Eventually, however, when the "average" has shifted well beyond "normal," ecosystems may have trouble persisting.[16]

The Role of Temperature

Temperature and its distribution are important determinants of plant productivity and survival. Temperature range exerts three classes of effects on plants: 1) low temperatures can damage plant tissues, causing die-offs during unusual extreme events and controlling the northward or altitudinal migration of plants; 2) in intermediate ranges, temperature governs the rates of photosynthesis, respiration, the growth and development of seeds, and other processes; and 3) high temperatures may stress plants to the limits of their ability to withstand heat and moisture loss, thus controlling plant distribution and migration (19). Seasonal distribution, diurnal cycles (i.e., the variation from night to day),[17] and the occurrence and timing of extremes (e.g., late spring frosts, early winter storms, and peak summer high and winter low temperatures) are all aspects of the effects of

[16] A shift upward in the mean temperature (with an unchanged standard deviation) will make heat waves of today more "average" in the future.

[17] A longer growing season based on temperature may actually prove beneficial for some plants because day length is a major factor in productivity.

Box 2-C—Climate Change and Coastal Fisheries

Background

The U.S. commercial, recreational, and sport fishing industries, worth an estimated $14 billion in 1988 (73), rely on the health of nearshore and coastal areas (such as tidal marshes, coral reefs, seagrass beds, mangrove forests, estuaries, and banks). Two-thirds of the world's fish catch, and many other marine spades, depend on coastal wetlands and estuaries for their survival (42). By far the greatest portion of U.S. commercial fisheries catches, with the exceptlon of those from Alaskan fisheries, are composed of estuarine-dependent spades. Ongoing alterations of critical habitat (such as geographic fragmentation and pollution) maybe exacerbated by climate **change.**

Much is yet to be learned about the marine environment and the long-term effects that humans have on it Understanding the breadth of environmental stresses that affect fish and coastal systems will be essential to forecasting how climate change may affect these valuable areas. During the 1970s and 1980s, populations of many commercially important estuarine-dependent fish plummeted. Human activities In the coastal zone are thought to have been responsible for many of the dramatic declines in fish populations. Overfishing has been implicated as a primary cause of the declines of some fish stocks, with some 42 percent of species in American waters considered to be overfished (52). The Atlantic cod fishery of the Grand Banks area has all but collapsed, triggering industry-related layoffs (primarily in Canada) of more than 30,000 people (75). Migratory species such as salmon, shad, herring, and striped bass have decreased due to a combination of habitat degradation and overfishing. The Chesapeake Bay's oyster harvest has declined 98 percent from the levels of 100 years ago due to disease, over-exploitation, predators, and habitat degradation (18). Neatly half of the Chesapeake's wetlands and seagrass meadows, which serve as primary nursery habitat for many migratory species, have been destroyed. Such destruction will adversely affect future fish populations.

The fishing industry from Southern California to Alaska is experiencing similar troubles as a result of overfishing, the damming of spawning rivers, water-quality degradation from logging, and other anthropogenic

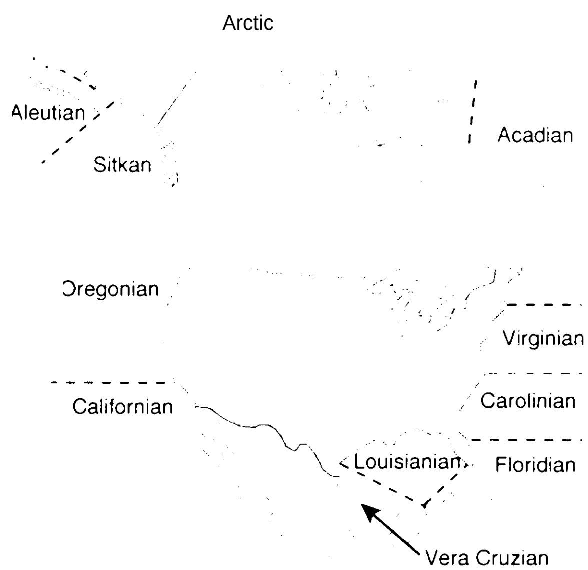
(Continued on next page)

temperature on plants. Length of the growing season is also very important, particularly for agricultural crops. Seed production generally requires a certain number of days with a temperature above freezing, often expressed in terms of degree-days. At northern latitudes, the growing season may not be long enough for some species to set seeds. Longer growing seasons in a warmer climate could boost productivity of trees and other plants, especially those that could tolerate erratic spring and fall weather (e.g., early or late hosts). Seeds of many tree species, including conifers, need to be chilled for particular periods before they will germinate (17,21), so a shortened Cool season could be detrimental to such species.

In addition to the numerous effects of temperature on vegetation, temperature exerts other direct and indirect influences on animals. Higher-than-usual temperatures can adversely affect the reproductive success of many birds, mammals, and insects (26). Increased water temperature limits the availability of oxygen in the water and, in turn, reduces the amount of oxygen available to fish and other aquatic organisms (87). For many fish species, ambient water temperature is critical for survival (see box 2-C). In addition, temperature increases can actually reduce the number of species in a given ecological community (87), though total biomass may increase.

Warmer temperatures could allow some insects, including various agricultural pests, to survive winters farther north than they now do. For example, the potato leafhopper, which is a pest on soybeans and other crops, now overwin-

Box 2-C-Climate Change and Coastal Fisheries-(Continued)



activities. In Alaska, where the seafood industry employs 23 percent of the State's work force, this could prove to be a major problem. More than half of the Nation's seafood harvest comes from Alaskan waters.

scientists have hypothesized that climate warming is likely to alter the distribution and reproductive success of coastal species (77). Many marine species are sensitive to narrow temperature variations. Water temperature controls the respiration and reproduction rates of fish. Changes in temperature can also affect the geographical distribution of species range because some species will thrive in warm waters, while others function effectively only in cooler waters. Changes in stream flows will also be important because they can alter the salinity of coastal bays and estuaries. The interactions of temperature and salinity determine the "tolerance zone" for most fish species. Anadromous fishes-which swim upstream to spawn, such as salmon—also depend heavily on stream flow and water quality (33). If these are altered by climate change, there maybe serious effects on reproductive success. In ail these cases, climate change would be expected to alter the dose associations between species distributions and reproductive success, and the success of the fishery as a whole. Although it is difficult to estimate the magnitude of these changes, impacts could upset the stability of the commercial fishing industry on which many coastal residents rely.

Coastal areas have also been affected by human activities that contribute toxic pollutants and polluted runoff to marine waters. Runoff from developed and agricultural areas and overflow from storm-water systems adversely impact these areas. Nutrients cause algal blooms, which deplete oxygen available for fish and other organisms. Stressed species may become more susceptible to disease and predators. Shoreline construction and dams have also contributed to fishery population declines. Destruction of estuarine and coastal zones limits nursery and breeding areas, and dams prohibit fish from reaching upriver spawning grounds {see vol. 1, ch. 4, and vol. 2, ch. 4).

Regulatory attention has generally not addressed coastal zone management in light of the potential impacts of climate change. Harvest regulations, which are either inadequate or insufficiently enforced, seem unable to keep pace with the decline in fish populations (52). In short, too many fishermen are taking too many fish from overburdened ecosystems. Traditional fishery management is concerned primarily with a few major resources and tends to pay far less attention to the other ecosystem elements that fish depend on (77). Increasing concerns about ecosystem management (see vol. 2, ch. 5) and the upcoming reauthorization of the Magnuson Fishery Conservation and Management Act (P.L 94-265, as amended) and the Clean Water Act (P.L 92-500, as amended) offer opportunities to work toward improving fisheries and their habitat. Below, we highlight the regional importance of marine fisheries and identify particular problems (77).

Regional Characteristics of the U.S. Coastal Marine Fisheries

Acadian-Boreal (Newfoundland and southern Greenland to Cape Cod, MA)

- ***Cultural:*** Indigenous coastal people-New England clam diggers.
- ***Fishing:***
  - —7 percent of the Nation's commercial fisheries
  - —estimated value, $250 million in 1990
  - —multispecies trawl fishery
  - -32 percent of species estuarine-dependent
  - -important species include hard dam, soft dam, American lobster, sea scallops, northern shrimp, Atlantic cod, butterfish, cusk, flounder, haddock, red and white hake (silver hake)
  - —Atlantic cod most commercially important fish in 1989 (valued at $45 million)
- ***Common problems:***
  - -only remaining self-supporting U.S. salmon runs are in Maine
  - -lobsters are overharvested
  - -northern shrimp are at maximum harvest and subject to environmental variability y, especially when waters are warmer

Virginian-Mid Atlantic (Cape Cod, MA, to Cape Hatteras, NC)

- ***Cultural:*** Indigenous coastal people--Chesapeake Bay watermen.
- ***Fishing:***
  - -estimated value, $500 million in 1990
  - —11 percent of the Nation's commercial fisheries
  - —most important species are blue crab and surf and ocean quahog
  - -Chesapeake Bay fish: 87 percent are estuarine-dependent
- ***Common** problems:*
  - -region is the most urbanized and densely populated in the United States
  - -disease, overharvesting, predation, and pollution are rampant-responsible for reductions in harvestable shellfish, forcing many watermen out of business
  - -second to the Gulf of Mexico in the number of point sources of pollution
  - -striped bass began a precipitous decline in 1973

Carolinian-South Atlantic (Cape Hatteras, NC, to Cape Canaveral, FL)

- ***Fishing:***
  - —3 percent of the Nation's commercial fisheries
  - -estimated valued, $189 million in 1990
  - —94 percent of species estuarine-dependent
  - -over half of this harvest fromestuarine-dependent species
  - -most important species indude Atlantic menhaden, bfue crabs, and penaeid shrimp
- *Common problems:*
  - -application of pesticides and fertilizers to extensive commercially harvested forested wetlands
  - -degradation of shellfish habitat due to agricultural runoff and septic system overflow

FloridIan-West Indian (Cape Canaveral to Key West, FL, and West Indies)

- ***Fishing:***
  - -values for individual species are not observed
  - -important species include the Queen conch, spiny lobster, Nassau grouper, and more than 100 reef fishes

(Continued on next page)

Box 2-C-Climate Change and Coastal Fisheries-(Continued)

- *Common problems:*
  - -growing human populations, greater demands, and technological improvements in catch
  - —virtually all assessed reef-fish stocks are overharvested
  - -major tropical storms, including hurricanes, generally affect the area

Louisiana-Gulf of Mexico (Northern Gulf of Mexico from Central West Florida to South Texas)

- *Fishing:*
  - —17 percent of the Nation's commercial fishery (with Vera Cruzian)
  - —estimated value, $648 million in 1989
  - -leading seafood producer among regions
- *Common problems:*
  - -subject to devastating floods, tornadoes, hurricanes and tropical storms, erosion, land subsidence, saltwater encroachment, and sedimentation
  - -second-fastest growing population rate of all regions
  - -more point sources of pollution than any other region
  - —application of pesticides to agricultural lands is the highest among all regions

Vera Cruzian-West Indian (South Texas to Yucatan Peninsula)

- *Fishing:*
  - —fourth leading U.S. port in fisheries value
  - -major commercial species are similar to those of the Gulf region
- *Common problems:*
  - -hurricanes and intense thunderstorms

California-Subtropical Eastern Pacific (Southern California (Los Angeles basin) southward to Mexico and Central America)

- *Fishing:*
  - --major commercial species include Pacific sardine, northern anchovies, and Jack mackerel
- *Common problems:*
  - -most wetlands already lost; restoration doubtful
  - -low-lying coastal areas subject to sea level rise

Oregonian-Temperate Eastern Pacific (California north of Los Angeles to British Columbia)

- *Fishing:*
  - -estimated value, $337 million in 1989
  - -one-fifth of catch estuarine-dependent species, especially Pacific salmon (Chinook, coho, sockeye, pink and chum)
  - -commercial landings of salmon valued at $140 million
  - --other important species include northern anchovies, Pacific sardine, Jack mackerel, and groundfish (flatfishes, rockfish, including Pacific whiting, sable fish, Dover sole, widow rockfish, and others)
- *Common problems:*
  - --conflicts among fishermen, the Fisheries Council, various States, Canada, and foreign fisheries regarding the allocation of resources
  - -worsening freshwater (spawning) habitat has been the main cause of the salmon decline, and wild coho stocks of the lower Columbia River were recently declared extinct

Sitkan-North Pacific (British Columbia to base of Alaska Peninsula)

- *Fishing:*
  - —*56* percent of the Nation's commercial landings of fish (with other Alaskan fisheries)

—estimated value, $1.5 billion in 1990
—5.4 billion pounds (2.5 billion kg) landed in 1990 (with other Alaskan fisheries)
—76 percent of species estuarine-dependent
-most important species include Pacific salmon, Pacific herring, Pacific halibut Gulf groundfish (Pacific cod, stablefish), king crab, and tanner crabs

- Common problems:
  -some rookeries threatened by fishery operations
  —Exxon Valdez oil spill severely contaminated coastal areas

Arctic-Boreal/Arctic (Southeast Bering Sea to Chukchl and Beaufort Seas and Canadian archipelago)

- Cultural: Coastal indigenous people-Eskimo, Aleute
- *Fishing:*
  -most important species include Pacific salmon, Alaska pollock, Pacific herring
  —Pacific salmon fisheries rank as the State's largest nongovernmental employer
  -provides an integral part of Alaska's native culture and heritage
- *Common problems:*
  -some stocks (chinook and coho) maybe harmed by foreign high-seas catches, and some salmon maybe regionally overfished
  -destruction of spawning and rearing habitat
  -human population in this area is expected to increase by 380 percent between 1960 and 2010

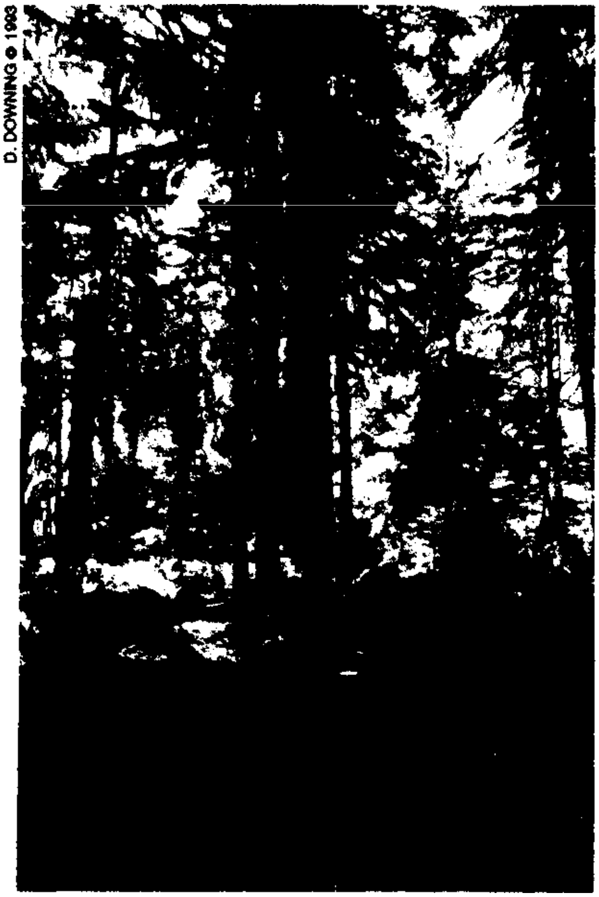
Aleutian-North Pacific (Alaska Peninsula base to Aleutian and Pribilof Islands and including southwest Bering Sea)

- *Fishing:*
  -estimated value of groundfish, $352 million in 1990
  --dominant groundfish groups are walleye pollock, flatfishes (Yellow sole, rock sole, other), Pacific cod, Atka mackerel, and shrimp
  —Alaska king crab value, $88 million in 1990
- *Common problems:*
  –*The* U.S. fishery for shrimp in Alaska is at a low level, and potential yields are not well-understood (91)

insular-lndo Pacific (Tropical Indian and Pacific Oceans; not shown in figure)

- *Cultural:* Coastal indigenous people-Papuan, Micronesia, and Hawaiian
- *Fishing:*
  —7 percent of the Nation's commercial fisheries taken in the Pacific United States and Hawaii
  -major species include invertebrates species (spiny and slipper lobsters; gold, bamboo and pink corals), bottom fish (snappers, jacks, groupers, Pacific armorhead), tropical tunas (yellowfin and skipjack), and albacore
- *Common problems:*
  -coastal pollution
  destructive fishery technologies (explosives, poison, etc.)
  -overfishing by foreign fleets
  -ambiguous application of Federal environmental laws

SOURCES: M.R. Chambers, "U.S. Coastal Habitat Degradation and Fishery Declines," In: *Transactions of the North American Wildlife and Natural Resources Conference* (Washington, DC: The Wildlife Management Institute, in press); U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS), *Our Living Oceans, The First Annual Report on the Status of the U.S. Living Marine Resources*, NOAA Technical Memo, NMFS-F/SPO-1, 1991; C.G. Ray, G. McCormick-Ray, and F.M. Potter, *Global Climate Change and the Coastal Zone: Evaluation of Impacts on Marine Fisheries and Biodiversity of the U.S.*, contractor report prepared for the Office of Technology Assessment, 1993.



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Fo a m de orga m nd sp C u la hıp d ti ns m g pla and a ma sy m Chang h nt m sph CO d g ifi affe th h a th and p odu ty va u omp h nd ma h sy m

ters in only a small area of the southern United States along the coast of the Gulf of Mexico. Warmer winter temperatures could greatly expand the overwintering range, allowing for much larger populations to develop in the spring, and potentially leading to increased plant damage (94).

The Role of *Precipitation and Soil Moisture*

Precipitation-or more precisely, soil moisture (the result of a combination of precipitation, infiltration, runoff, and evaporation--directly affects plant growth through its role in photosynthesis. Although average annual precipitation is often used to characterize climate zones, the seasonal distribution is more significant than the annual total. Adequate moisture during the growing season is critical. Seeds need moisture to germinate, and young plants-both annuals and perennial s-are often quite sensitive to drought. Vegetation may respond by defoliating, which reduces water and nutrient demand, helping plants survive dry periods. Precipitation during the growing season controls wood growth as well as the size and maturation time of seeds (21, 42). Decreases in soil moisture can slow growth, interfere with reproduction, and cause plants to die early. Increases in soil moisture are less likely to cause harm unless the soil in normally dry areas becomes saturated with water for extended periods. Standing water can drown the roots of plants not adapted to wetlands by interfering with normal respiration; extended saturation of roots may kill the entire plant.

Direct effects of moisture on many land animals may often be less important than the indirect effects-that is, moisture affects plant growth, which then affects the availability of food and habitat (86). However, moisture does play a critical, direct role in the natural history of invertebrate species (e.g., snails) and is essential to the survival and reproduction of amphibians (105). Fish and other aquatic organisms that inhabit rivers and streams can be threatened by either too little water during drought periods or too much runoff flowing into streams. During periods of high precipitation, water may become turbid, interfering with the health and functioning of the aquatic ecosystem. Moisture is also important to many microorganisms and fungi, including many that contribute to human disease or are considered forest or agricultural pests (described in more detail below and in vol. 1, ch. 6, and vol. 2, ch. 6).

sunlight

The amount of available sunlight, or *solar irradiance,* that strikes vegetation is an important variable in photosynthesis and productivity. Individual plants or species that make up the canopy, those near the edges, or those growing in clearings receive more light, whereas those in the understory are better adapted to lower light levels. Solar irradiance varies regularly from season to season and from latitude to latitude. Cloud cover also affects the quality and quantity of solar irradiance and its distribution over time, allowing less sunlight to reach the surface on cloudy days. If climate change is accompanied by increased cloudiness, as some models predict, overall plant productivity could decline. Water stress and high temperatures may also affect plant response; however, plant response to changes in solar irradiance is complex and difficult to predict (19).

In addition to the total amount of solar irradiance, the number of hours of sunlight per day (day length, or *photoperiod)* plays a role in plant fictions such as flowering and the setting of fruit, and influences the rising of sap in deciduous trees, such as sugar maple, in spring. Light quality may also affect productivity. For example, cotton depends on very regular day lengths, which only occur in southern latitudes. Plant species that might migrate northward as the climate warms may not be able to reproduce as effectively because day length is longer at northern latitudes during the summer and drastically reduced during the winter (41). On the other hand, adaptation to a shorter photoperiod may limit northward movement.

Increased CO_2

Rising concentrations of atmospheric CO_2 may affect the rates at which plants grow, respire, use water, and set seeds. This is known as the CO_2 *fertilization effect (see* box 2-D). Numerous laboratory experiments and intensively managed agricultural systems that have been studied suggest that CO_2 has the potential to boost plant growth and productivity by speeding the rate of photosynthesis, relieving nutrient stress (by improving efficiency of nutrient uptake and use), increasing water-use efficiency, decreasing respiration (which is a major source of water loss), slowing the rate at which leaves die, and speeding the development of seeds (27,42, 66,68,69, 93).

Theoretically, the fertilization effect could compensate for the water stress faced by plants in areas that become warmer and drier due to climate change, and might actually increase the total global biomass (41). On the other hand, various studies have suggested that in some settings, there may be limits to and even detrimental effects from increased CO_2. For example, changes in the amount of carbon in plant leaves affect nutritional quality (65), which could mean that foraging animals would have to eat more leaves to gain the same amount of nutrition. Increased CO_2 may also cause starch to accumulate in plant leaves to such high concentrations that it could actually harm the plant by interfering with photosynthesis (50), though there is no field data to support this.

Numerous complex factors interact to determine the extent to which fertilization actually occurs in natural ecosystems, and many uncertainties about the overall impacts remain. Plant responses to CO_2 vary according to species and stage of development, as well as to water and nutrient availability (42). Some plant species already use CO_2 efficiently and will not receive much of a boost, whereas other species are now limited by their inefficient use of CO_2 and could profit from higher atmospheric concentrations.

Plants may experience the greatest productivity boosts from increased CO_2 when other nutrients are plentiful (7). Thus, for example, field studies have demonstrated that higher CO_2 concentrations boost productivity in Chesapeake Bay salt marshes, where water entering the bay is rich in nutrients (2, 27, 28, 107), but CO_2 fertilization does not appear to be significant or permanent in nutrient-limited tundra and other arctic ecosystems (32, 68). Few other ecosystem types have yet been tested in the field. Intensively managed agricultural systems, in which nutrient deficien-

Box 2-D-Coping with Increased CO_2: Effects on Ecosystem Productivity

Climate, particularly the combination of temperature and moisture, largely determines where plants grow (14), and vegetation, in turn, is key to the distribution of animal species. Generally, climate belts vary within the United States from humid and damp in the Southeast and Northeast to moderately dry in the central regions, to arid in much of the West except for a humid belt along the Pacific Coast from northern California to Washington. Temperature and precipitation maps of the United States reveal bands across the Nation from north to south for temperature, and east to west for precipitation. Vegetation growth, in type and lushness, varies with temperature and altitude, but in all cases, solar irradiance is critical to the productivity of living things.

The sun provides the energy that fuels ecosystems; this energy is transformed through the processes of photosynthesis and photorespiration. During photosynthesis, plants use water and the energy from sunlight to convert carbon dioxide (CO_2) and other nutrients into organic matter and oxygen. This process is dependent on the concentration of CO_2 In the air (i.e., ambient CO_2, and, therefore, changes in normal CO_2 levels may affect photosynthesis and, likewise, plant growth. External environmental factors, such as temperature and the availability of nutrients, may modify photosynthesis as well. The output of organic matter by an ecosystem is characterized as its biological or *primary, productivity.* Linked to primary productivity is *nutrient cycling-the* absorption by plants of vital nutrients (e.g., carbon, nitrogen, and phosphorous) and their subsequent conversion into usable forms.[1] The combination of energy and nutrient cycling in vegetative systems determines the nature of the assemblage of plants and animals in a given area. Certain types of plants, growing in certain conditions, have higher primary productivities than others. Ecosystems that are highly productive often support both large numbers of other organisms and many diverse species—that is, they are characterized by high secondary *productivity* and high biodiversity.[2] Productivity is also key to *carrying capacity—the* number of organisms that a particular area can support. Carrying capacity can vary from year to year based on many factors, including climate,

1 Carbon is derived from CO_2 through photorespiration; nitrogen andphosphorousare taken up from the soil and converted to usable forms during the same process.

2 Although definitions vary, biodiversity generally refers to the "variety and variability among living organisms and the ecological complexes in which they occur" (89).

cies can be remedied by adding fertilizers, maybe more likely to receive a productivity boost from additional CO_2 than are natural ecosystems. Many complex interactions determine to what extent, if any, the CO_2 fertilization effect documented in laboratory studies will occur in natural ecosystems. The responses will likely vary so much fromn ecosystem to ecosystem and location to location that there cannot be a simple answer to the question of whether it will present a net benefit or a net harm.

■ Indirect Climate Impacts Through Stressors

Climate will also have numerous secondary impacts. Increases in herbivores, disease, and fires, which play an important and visible role in mediating the near-term effects of climate change on communities and ecosystems, could result. For example, although few trees in a forest may die outright due to heat or drought, it is likely that many trees will sicken and become more susceptible to insects and disease. At the same time, trees in decline will provide more fuel for fires (83). The extent to which an area is stressed by anthropogenic activities, such as land clearing and pollution, will also influence the effects of climate change.

Insects anti Disease

Climate may affect the proliferation of insects and disease in numerous ways. Higher temperaand refers to the indivdual species or mix of species in a particular ecosystem. overall, however, ecosystem health and productivity is dependent on the availability of sunlight water, nutrients, and $C0_2$.

Considerable experimental evidence has shown that an increase in the atmospheric concentration of CO_2 has the potential to increase plant growth and ecosystem productivity (28). This expected effect of Increased plant productivity in the presence of elevated CO_2 concentrations is known as the "CO_2 fertilization effect," and it **is** expected to be particularly pronounced in the presence of plentiful supplies of light, water, and nutrients. Over the long run, this effect may help alleviate the rate of global warming by drawing excess $C0_2$ from the atmosphere (8), although researchers are uncertain about the extent to which this will occur (vol. 2, see box 8-B).

Plants vary in their response to CO_2 in part because of differing photosynthetic mechanisms—most species follow the C_3 pathway and some, the C_4 pathway. C_3 species (e.g., wheat, rice, soybeans, and all woody plants) are not yet fully saturated with CO_2 and may greatly increase their productivity, whereas C_4 species (e.g., *corn,* sorghum, sugar cane, and tropical grasses) are almost saturated with $C0_2$ and their productivity may not be much affected. Added productivity of C_4 species from doubled $C0_2$ may be in the O to 20 percent range, and in the 20 to 80 percent range for C_3 species. The differential effects of $C0_2$ could alter the dynamics of competition among species, with C_3 plants potentially prospering at the expense of C_4 species. In agriculture, this competition among plants may prove important. Because 14 of the world's most troublesome weed species are C, plants that occur amidst C_3 crops, enhanced $C0_2$ concentrations may make such weeds less competitive (73). However, many of the major weeds of corn (a C, crop) in the United States are C_3 plants; climate change may favor the growth of these weeds. Similarly, natural grassland ecosystems where C_4 grasses now dominate maybe invaded by weedy plants. Competitive success, however, does not depend solely on response to CO_2. Competition among species in natural ecosystems will continue to depend on the ability of species to tolerate soil, light, temperature, and moisture conditions. Because of the complex effects of competition among species it is by no means clear how the overall productivity of natural ecosystems will increase under elevated $C0_2$ (8).

SOURCES: B.G. Drake, "The Impact of Rising CO_2 on Ecosystem Production," *Water, A/r, and Soil Pollution,* vol. 64, 1992, pp. 25-44; P.M. Kareiva, J.G. Kingsolver, and R.B. Huey (eds.), *Biotic Interactions* and G/06a/Change (Sunderland, MA: Sinauer Associates, Inc., 1993).

tures could accelerate the growth rate of insects. If the number of warm days per year increases, the number of insect generations per year may increase. Also, the range of many insects is determined by cold winter temperatures. As described in the section above on temperature impacts, milder winters could allow insects such as leafhoppers (agricultural pests) to spread north of their present range. Hot, dry conditions encourage the growth of numerous fungi in forests (such as *Armillaria mellea,* a fungus that causes root disease), which can cause widespread damage in many types of forests. Warm, humid conditions, which favor soil and leaf-litter organisms as well as decomposition, may encourage the growth of other fungi and insect pests, such as aphids, which can also be quite damaging.

Once stressed by heat or drought, vegetation may become more susceptible to pests (58). Changes in CO_2 concentration may affect the composition of leaves, potentially making them less nutritious, so insects might have to consume more to obtain the same amount of nutrients (8). Thus, damage from insects and disease might increase, and in some cases, the effects of climate change may become noticeable over the short term. Over the long term, damage from insects and disease may cause less-adaptable species to decline, potentially opening the way for exotic species to migrate into communities (21, 83).

Exfreme *Events*

Periodic but unpredictable events such as extended drought, storms, and fire are among the primary natural factors that shape ecosystems.

Severe storms accompanied by high winds and rain, hail, or ice may cause significant wind damage in forests, toppling older trees and leaving a trail of debris, but also clearing space for new vegetation to take root (see vol. 2, ch. 6). Storm damage may reduce habitat for birds and wildlife that prefer a dense forest canopy and little undergrowth, but could increase food and habitat for animals that thrive in mixed forests with cleared areas, such as deer. In coastal areas, tropical storms and their accompanying high winds and waves play an enormous role in coastal processes (see vol. 1, ch. 4).

The occurrence of fire is critical in determining vegetation types, successional history, and wildlife species in forests in more arid areas, such as prairie and chaparral, and in wetlands. Fire is important in maintaining prairie, but the control of fire has virtually eliminated most naturally occurring prairie areas. In some wetlands, including the Okefenokee Swamp and others along the Atlantic coastal plain, fire has played an important role in clearing shrubby growth and maintaining wetland vegetation. Under normal conditions, fire clears out forest undergrowth, damaging some trees but allowing new ones to take root, thus creating a more open stand of trees (see vol. 2, box 5-I).

Fire has been recognized for playing an important role in vegetation succession. In areas where fires have been suppressed and fuels have accumulated, however, fires may become so hot that they cause severe damage, and forests may regenerate slowly or not at all. For example, chaparral ecosystems in the foothills of California rely on fire to spur the growth of the shrubby plants that dominate the area; however, in areas where fire has been suppressed, a fire that does occur will be more damaging, and the regeneration of chaparral species maybe affected. Natural fire regimes are influenced by the frequency of lightning (which may or may not increase as the climate changes), the presence of hot, dry winds to carry a fire once ignited, and an abundance of dry fuel provided by the buildup of undergrowth or vegetation that has died from drought or disease, as well as by dry, living vegetation (22). Fires may increase under changed conditions, but the ability of species to regenerate in areas with less moisture, because of climate change, maybe reduced. Thus, recovery may not occur.

Anthropogenlc Forces

Climate change may serve to make species or ecosystems more susceptible to stresses from human disturbance. Human activities have become so widespread that they are now a pervasive influence on much of the environment. Agriculture, timber harvesting, road building, and urban development have fragmented the landscape, carving natural areas into ever smaller and less-connected patches (see vol. 2, box 5-E). This fragmented landscape may offer few opportunities for organisms to adapt to a changing climate. Fragmentation often isolates small populations of plants and animals, which may limit genetic diversity and make them less able to adapt to change over time. These small, isolated populations may also be prevented from moving to new and more favorable areas by barriers such as roads, buildings, or large cultivated fields. In addition, humans may respond to changes in climate by adopting land uses (such as more extensive cultivation) that further fragment the landscape, exacerbating the stresses on flora and fauna.

Human activities may also result in the introduction of weedy and nonindigenous species that flourish in the disturbed areas and that may eventually outcompete other species, leading to local extinctions and reducing the diversity of ecosystems. In areas where weedy or nonindigenous species already pose a threat to a particular species or ecosystem, the added stress of climate change may further tip the balance in favor of weedy species that thrive in disturbed conditions. Similarly, air pollution in urban areas, and in much of the Northeast, already threatens the health of many plant species. Climate change could further weaken individuals that are already stressed by pollution, and could make them more susceptible to insects or diseases.

Although climate change might not be the proximate cause of ecosystem harm, it could increase the potential for damage. In sum, climate change may exacerbate many other stresses, both natural and anthropogenic.

Direct Climate Impacts on Ecosystems

As temperature and moisture regimes change, climatic zones could shift several hundred miles toward the poles, requiring plants and animals either to migrate or adapt to a new climate regime. The rate of change will determine the degree of impacts: some species might be able to keep up with change, others could become extinct--either locally or globally (see box 2-E). The ability of a species to adapt will be critical to its survival. By the same token, the decline and disappearance of species that are unable to adapt will decrease the biodiversity of ecological communities. Such a reduction may leave the remaining species more vulnerable to catastrophic events. Ecosystems, the assemblages of plants and animals, are unlikely to move as units, but will instead develop new structures as species abundance and distribution are altered (42).

The general distribution of ecosystems is related to climatic conditions. The Holdridge life zones shown in figure 2-10 characterize regions of North America according to the general vegetative ecosystem suited to current climate conditions. Under climate change scenarios projected by four GCMS, this distribution of vegetation zones will shift significantly (34). There is general agreement among scenarios about the direction of change: the extent of tundra and cold-desert climate zones will decrease, and the area of potential forest and grasslands will increase. Despite this general agreement, there are qualitative differences, with dry forest types increasing under some climate scenarios, and moister forests increasing under others. Overall, as much 80 percent of the land in the United States may shift to a new vegetation zone (see fig. 2-11). Associated with such shifts in climatic zones could be large-scale disturbances to existing ecosystems.

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Alpine areas are awash in color when spring and surmmer flowers bloom.

Adjustment *of Species*

Natural adjustments to climate change could begin with the failure of some species to reproduce because flowering, fruiting, and seed germination-and in some animals, reproductive physiology or mating behavior-could be affected. All of those processes are particularly sensitive to climate. Reproductive failure might allow new species to invade, or give a competitive advantage to other species already present. Thus, a gradual adjustment could occur, although in

Box 2-E—Responses of Natural Systems to Climate Stress: Adaptation, Migration, and Decline

Responses of individuals and communities to climate stress fall into three basic categories: adaptation, migration, and decline and die-back. The extent to which individuals and communities respond may depend on the rate and magnitude of climate change.

Adaptation

It is difficult to predict which species, populations, communities, ecosystems, and landscapes will prove most able to cope with climate change because of the many variables and uncertainties that exist. However, biological diversity affords populations the ability to adapt to changes in the environment by serving as a natural protection against shocks and stress. "The rule that there is security in diversity is an axiom of ecology as well as finance. . . . Biological diversity is a natural protection against surprises and shocks, climatic and otherwise. Among diverse species will be some adapted to prosper in a new landscape in new circumstances" (21).

In species with diverse gene pools, the chances will be greater that some individuals will possess a combination of genes that is useful in new environments, such as genes that determine drought resistance and tolerance to extreme temperatures or salinity. These individuals will be the most likely to survive and pass along adaptive characteristics to their offspring. At the community level, diversity may also increase the chances for survival. For example, a forest stand composed of a single species or of trees that are all the same age may be less able to withstand climate change than a forest composed of several species within a range of ages. Biodiversity is generally considered an important trait at the ecosystem level, too, because it increases the charms that the overall structure and function of an ecosystem will persist or adapt to changing conditions, even if some species that were formerly part of the ecosystem no longer remain (21).

Some species may prosper under climate change conditions, others maybe able to adapt relatively quickly, and still others may prove unable to adapt at all and may face extinction. As a result, ecosystems may change as different plant species become dominant and different animal species become associated with altered habitats (21). Species in varied landscapes may be able to find microclimates within their current ranges that are suitable, and some species may even thrive and expand their ranges. Species already adapted to disturbed environments (e.g., weedy species) may be particularly resilient to changes in climate. On the other hand, species with extremely specific and/or narrow habitats may be more at risk to changes in climate. In addition, species on the fringe of habitats, in transitional zones, may also experience greater stress from the impacts of climate change because these species may not be well-established. On the whole, some species maybe restricted by a variety of biological and physical limitations, but others will be able to adapt to the conditions brought on by climate change.

Certain wildlife species may be able to alter their diet in favor of other, exotic but newly available plant species. White-tailed deer, mule deer, moose, elk and other species benefit from human activities that disturb ecosystems and alter habitat (22). if, for example, climate change contributes to the conversion of a dense, forested habitat to a more open area, species such as these would likely benefit. Similarly, some birds, such as robins, starlings, and gulls, may adapt easily to alterations in habitat caused by climate change (22). These species tend to feed on a variety of different organisms and are territorial and aggressive in nature. They are very good at vying for resources with less competitive and smaller birds.

Migration

Some communities and ecosystems might have to migrate to survive the environmental conditions that could result from climate change. Most species of vegetation and wildlife have the ability to migrate to some extent. However, adverse conditions, such as landscape fragmentation, may limit this ability (see vol. 2, ch. 5). In addition, the ability of a species to migrate depends not only on environmental conditions but on dispersal rate. Animals can generally disperse much more quickly than plants (22). However, because wildlife is dependent on vegetation for survival, many species are forced to migrate only as fast as vegetation does (94). Therefore, the health and survival of many species will be dependent on the response of vegetation to climate change.

Dispersal rates for vegetation are considerably slower than the projected rate of climate change, and, therefore, some species will not be able to migrate as fast as their corresponding climatic regimes. For example, most North American tree species can migrate at 12 to 25 miles (20 to 40 kilometers) per century, but climate regimes are expected to migrate at much faster rates, in some cases by at least an order of magnitude (106). In particular parts of the United States, climatic regimes may shift hundreds of miles by as early as the middle to the end of the next century (43, 74). Because some species will be unable to keep up with the pace of climate change, their range may be reduced, or they may become extinct.

Coastal and estuarine wetland vegetation will likely attempt to migrate inland as the sea level rises. Their success in migrating will depend on the steepness of the coast and obstructions to migration that might exist, such as rocky areas and human-built structures. Wetlands fringing the playa lakes of the Southwest may retreat along with the water levels if increased evaporation, in a hotter and drier climate, causes water levels to drop. Alpine tundra will likely migrate toward higher altitudes as lower areas become warmer and drier.

In all of these cases, wildlife and other organisms that are dependent on these ecosystems for survival may attempt to migrate as well. The least Bell's vireo, an endangered species completely dependent on riparian vegetation for survival, may lose a great deal of habitat if inland drying occurs (22). The jack-pine forest in northern Michigan, which provides critical habitat for the endangered Kirtland's warbler, could die off and be replaced by a sugar maple forest in as few as 30 years under climate change conditions (11).

In each case, the ability to migrate will be limited by adjacent land-use patterns and the availability of areas to which organisms can migrate. "Barriers," such as roads, cities, and agriculture, degrade habitat quality and limit the ability of vegetation and wildlife to move or spread. Roads may pose a formidable physical barrier to animal migration, and even plants may have difficulty "moving" across roads if their seeds are too heavy to be dispersed easily and over large distances by wind. Vast expanses of suburban developments now occupy sites that formerly could have offered either suitable destinations or pathways for migration of plants and animals from one locale to another. Many animals will not cross seemingly small obstructions, such as railroad clearings or roads, to get to nearby suitable habitat (22). Agricultural land and other highly managed areas prevent species from naturally establishing themselves. In general, the ability of plants and animals to migrate in response to climate change is largely affected by anthropocentric influences and factors. Nevertheless, many species will be sufficiently resourceful to migrate successfully, and some may even thrive and expand their ranges.

Decline and die-back

If climate change is rapid or severe, some species, ecosystems, and landscapes may not be able to adapt Changes in climate may cause severe loss of function or value in certain species, ecosystems, and landscapes, or may result in the disappearance of certain species or entire ecosystems. Just as human land-use patterns may limit migration, they may also ultimately limit the chances for some species or ecosystems to survive. Some species are well-suited to a very narrow set of environmental conditions, but lack characteristics that would allow them to move or adapt easily to new environments. When human activities reduce or eliminate their normal habitats, these species are likely to show signs of stress leading to decline or die-back.

In forest systems, decline and die-back occur when a large proportion of a tree population exhibits visible symptoms of stress, unusual and consistent growth decreases, or death over a large area. Such distinguishing characteristics can be irregular in distribution, and discontinuous but recurrent in time. In all cases, however, decline and die-back are the result of complex interactions of multiple stress factors (83). Some common abiotic factors include drought and low- and high-temperature stress. Biotic agents include defoliating insects, root-infecting fungi, and borers and bark beetles. Typicalty, declines are initiated by an abiotic stress, with mortality ultimately caused by a biotic stress agent.

(Continued on next page)

Box 2-E—Responses of Natural Systems to Climate Stress: Adaptation, Migration, and Decline-(Continued)

More often than not, the decline and die-back scenario is a direct or indirect response to a change in some climatic variable. Changes in precipitation and temperature patterns have been shown to have an interactive and sequential influence on the health of forest systems. Drought conditions tend to enhance the possibility of insect attack. For example, sugar maple in northern forests is extremely sensitive to extreme changes in temperature. Moist, warm weather is particularly conducive to the spread of Eutypella canker, a serious stem disease, whereas drought periods favor the spread of *Armillaria* root decay; wind damage and sudden temperature drops significantly favor certain cankerous fungi, and the Iack of snow cover can result in deep root freezing (83). Nevertheless, these phenomena have sufficient common characteristics in various forest tree species to allow for some generalization; changes in climate will almost certainly exacerbate existing stresses, further influencing forest decline and die-back.

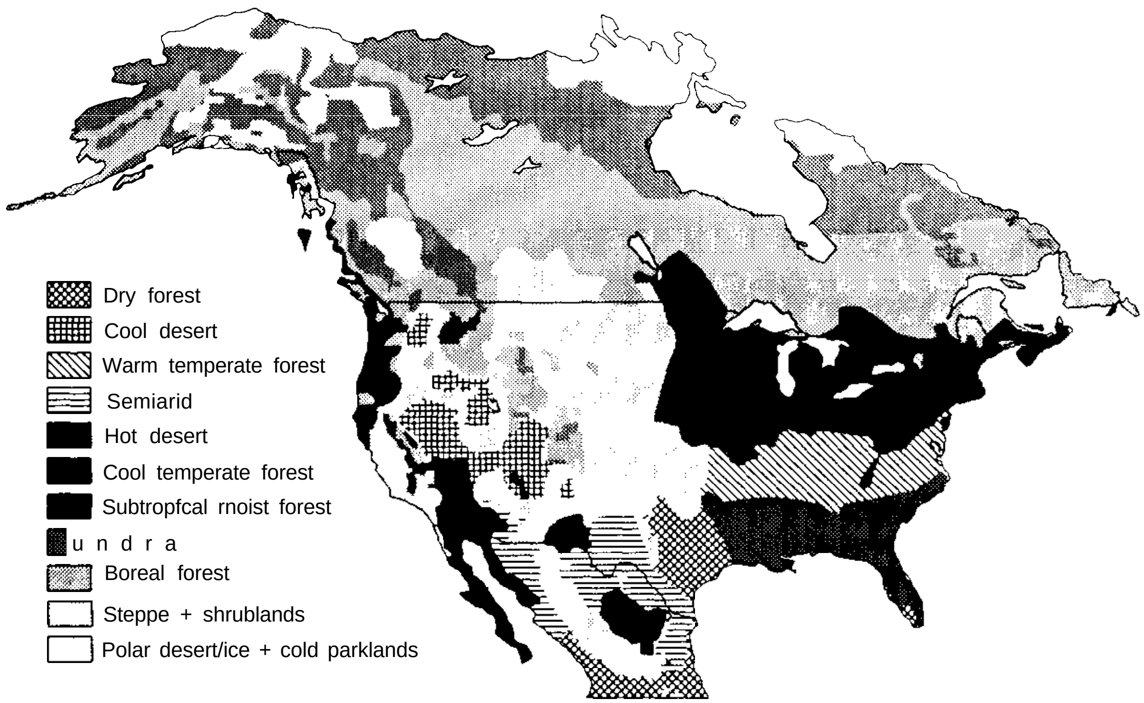
Some ecosystems will be influenced by changes in sea level rise. For example, coastal wetlands have been able to keep pace with a sea level rise of approximately 0.04 inches (1 mm) per year for the past 3,000 years, which is the rate at which many marshes are able to accumulate material. However, climate change is sure to increase the rate at which sea level rises, which may ultimately drown these wetlands (98). Likewise, alpine and arctic ecosystems may shrink and, in some sites, disappear if the amount and speed of climate change exceed the rate at which these systems can migrate upslope. On the whole, the rate at which climate change occurs will have a direct effect on the rate at which ecosystems experience declines in population and die-back responses.

SOURCES: P.M. Kareiva, J.G. Kingsolver, and R.B. Huey (eds.), *Biotic Interactions and Global Change* (Sunderland, MA: Sinauer Associates, Inc., 1993), 559 pages; R.L. Peters and J.D.S. Darling, "The Greenhouse Effect and Nature Reserves," *Bioscience*, December 19S5, pp. 707-17; C. Zabinski and M.B. Davis, "HardTimes Ahead for Great Lake Forests: A Climate Threshold Model Predicts Responses to CO_2-induced Climate Change, " in: *The Potential Effects of Global Climate Change on The United States, Appendix O: Forests* EPA-230-95-89-054, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 19S9).

some areas, or for some species, slow processes of seed dispersal, soil development, and achievement of sexual maturity may curtail adaptation. Pollen records suggest that temperate forests can migrate at approximately 62 miles per century, but the correlated growing-season conditions may shift by 200 miles for every 4 OF (2 'C) of warming, so even in the lower range of climate change predictions, some tree species might not be able to keep up. Modeling results suggest that if a forest includes some species that are better adapted to a new climate, those species may become dominant, but if none of the species are better adapted, the whole forest might decline. However, climate change is unlikely to decimate vegetation and make land barren, except in limited areas that are now arid and that may become even drier. Rather, ecological communities are likely to change as rapidly moving and widely dispersing species (e.g., weeds) increase in number, while slower-moving species decline and disappear (21).

The adjustment process will not occur uniformly across species, communities, and ecosystems. Plants or animals attempting to migrate to new areas may face competition from those that still remain. Some migrators may be able to compete effectively, and others may not. For example, wetland vegetation may attempt to take root further inland as sea level rise inundates coastal marshes, but existing inland plants that survive may temporarily block the path. Migration may also be blocked by areas rendered unsuitable as a result of human use. Some wetland species may be more capable than others of establishing themselves among the inland vegetation. Thus, many species, as well as ecosystem processes and interactions, may be reshuffled,

Figure 2-10-The Distribution of Holdridge Life Zones Under Current Climate Conditions



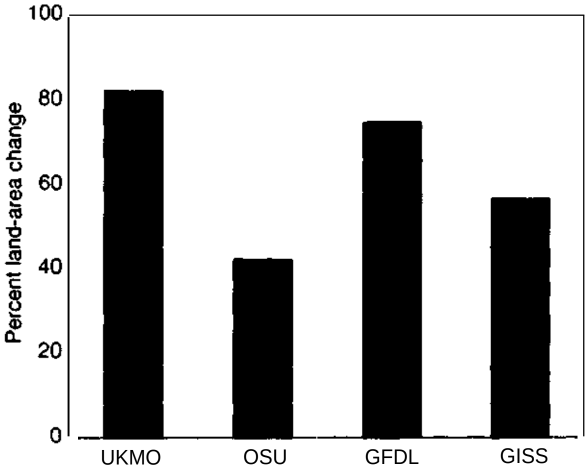
SOURCE: Office of Technogy Assessment, 1993, adapted from L.R. Holdridge, Life Zone Ecology(San Jose, Costa Rica: Tropical Science Center, 1987), and W.R. Emanuel, H.H. Shugart, and M.P. Stevenson, "Climatic Change and the Broad Scale Distribution of Terrestrial Ecosystem Complexes," Climatic Change, vol. 15,1985, pp. 75-82.

especially at the boundaries of current ecological zones, where ecosystems are the least mature and the most stressed (21). However, plants that are capable of migrating or adapting may not necessarily be the most desirable. Climate change could lead to an increase in less-valued species and a change in ecosystem composition.

Development of Asynchrony

The migration of vegetative species could put many organisms "out of sync' with their environments and disrupt many symbiotic relationships. As plants migrate inland and upland, pollinators and other vectors that assist in the reproductive process may not move at the same rate. If insects and birds are left behind, plants will face significant losses in populations, and some may become extinct. This may be especially true for organisms with very specific ranges, whether they be limited by topography, precipitation, or temperature. In addition, insects and birds may arrive at their migratory destinations prematurely, before feeding and nesting conditions are optimal, or too late, after resources have been exhausted. Organisms will be exposed to different and varying conditions, such as photoperiod, intensity of sunlight, and temperature, unlike what they are currently acclimated to, which may affect reproductive capabilities as well. In addition, some plant species may alter nutrient cycles and other processes in order to adapt to new soil and moisture conditions. This could not only adversely affect the health of plants, but could reduce their nutritional value, thereby affecting the health of the wildlife that depends on them for sustenance. Marine species will face similar

Figure 2-n-Percent of U.S. Land Area Shifting Holdridge Life Zones After CO_2 Doubling



NOTE: UKMO-United Kingdom Meteorological Office, OSU-Oregon State University, GFDL=Geophysical Fluid Dynamics Laboratory, and GISS=Goddard Institute for Space Studies.

SOURCE: P.N. Halpin, "Ecosystemsa at Risk to Potential Climate Change," contractor report prepared for the Office of Technology Assessment, June 1993.

D. DOWNING © 1993

Many species of birds, like this Clark's nutcracker, are dependent on specific habitats that provide sustenance and cover. Fragmentation of these areas could have a dramatic impact on populations unable to locate mating, nesting, feeding, and over-wintering habitat.

difficulties because most fish require specific conditions for reproductive activities to occur at optimum rates. Anadromous fish (those that swim into freshwater streams from the sea to spawn) may be most affected as salinity in intertidal waterways is altered due to sea level rise. On the whole, the migration of vegetation in response to altered climate and the subsequent response of insects, birds, and other organisms could have significant impacts on ecosystem structure, function, and value.

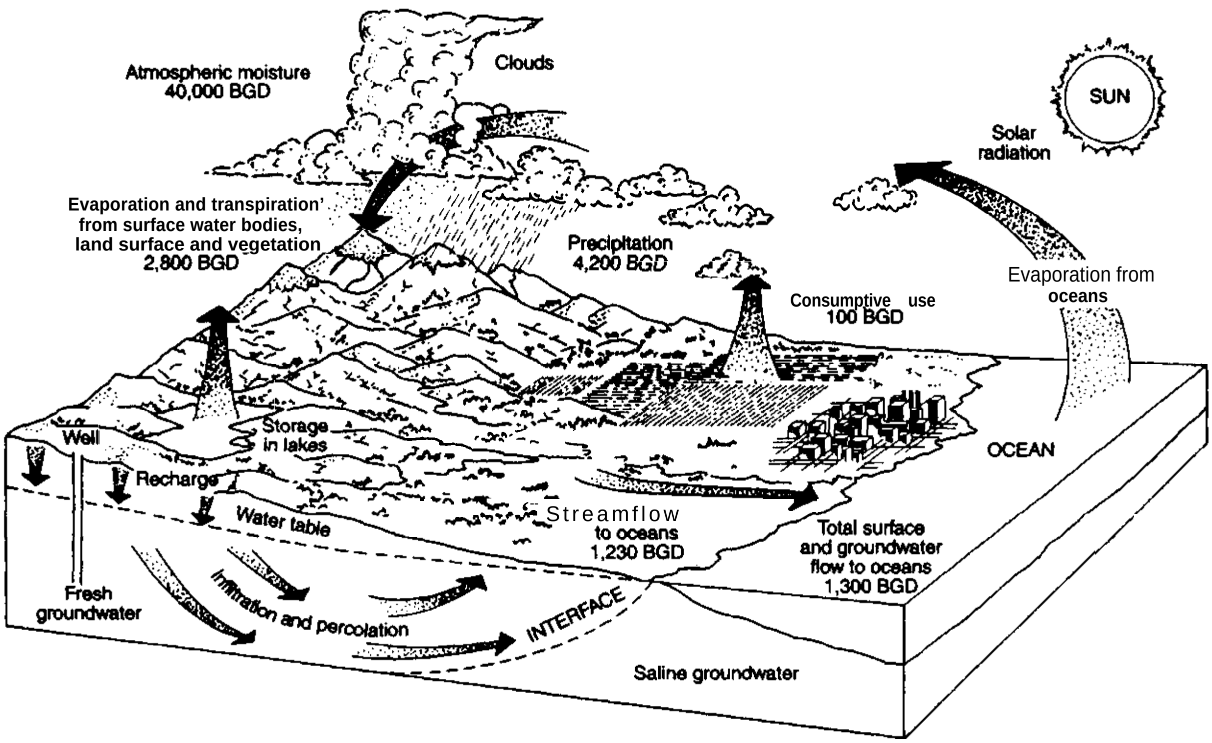
Interactions Among Climate, Ecosystems, and the Physical Environment

Climate change will affect living organisms both directly and indirectly, as described above, but it will also affect the processes of the physical environment in which they exist-soils and nutrient cycling, the hydrologic cycle, and photorespiration. Effects on the physical environment and living organisms will interact and cause further modifications to the environment and the organisms. Because the various biological and physical processes are intricately interconnected, with many feedbacks among them, it is difficult to predict what the overall effect of climate change will be. The following sections suggest the range of interactions between climate and the biological and physical processes it affects.

Interaction of Water Resources and Ecosystems

Water influences ecosystem function, but ecosystems, in turn, influence the flow of water through the hydrologic cycle (see fig. 2-12 and vol. 1, ch. 5). Water falls to the Earth's surface in the form of precipitation. Some water stays on the surface and evaporates relatively quickly. Some percolates into the soil and is taken up by vegetation, from which it is eventually transpired through the processes of photosynthesis and respiration. The remaining precipitation moves from upland to low-lying areas-on the surface, as shallow groundwater flow toward rivers or streams, or by infiltrating more deeply into and through aquifers, eventually emptying into rivers,

Figure 2-12—The Hydrologic Cycle Shows How Water Moves Through the Environment



NOTE: BGD = billions of gallons per day, To convert gallons to liters, multiply by 3.785.

SOURCE: Office of Technology Assessment, 1992.

lakes, and oceans, from which it eventually evaporates-and the cycle begins again.

The extent to which water evaporates, discharges to surface water, seeps into the ground, or remains on the surface depends on the amount and form of precipitation, the temperature, the topography, the nature of soils (whether sandy or clayey, and the content of organic matter), and the types of vegetation. Vegetation moderates the cycle in several important ways: it adds to the organic matter of soils, increasing their water retention; roots and stems may physically anchor soils and slow the passage of water and channel water below ground, further reducing runoff; and canopies of leaves reduce droplet impact on the soil and affect the rate of evapotranspiration. Because of these interactions, changes in vegetation may cause changes in the hydrologic cycle. For example, a semiarid grassland that is stripped of vegetation through overgrazing (by either wild or domestic herbivores) may lose some of its ability to retain water as plants no longer slow runoff or take up water to release it slowly later. The interaction of changes in the ecosystem and the hydrological system may eventually lead to desertification.

Climate interacts with the hydrologic cycle on different scales. Global average temperatures affect how much moisture can be carried in the air, how quickly clouds form, how readily clouds yield precipitation, and how much precipitation occurs and in what form (e.g., rain or snow), as well as the large-scale wind patterns that carry clouds from one region to the next. On a regional or local scale, temperature affects the rate at which water evaporates from the surface or transpires from plants. Temperature further affects the rate of evapotranspiration by influencing the form in which precipitation falls. Rain typically runs off soon tier it falls. Snow may remain on the surface for a considerable amount of time, with the delayed runoff supplying downstream and adjacent areas with water during the spring. Thus, global and regional changes in temperature and precipitation can affect the hydrologic cycle and the related ecosystem interactions in numerous ways.

The predicted changes in global climate will essentially increase the rate at which the hydrologic cycle occurs, although different hydrologic models yield rather different scenarios of what the regional results will be (79). As outlined above and in volume 1, chapter 5, total global precipitation is expected to increase 7 to 15 percent, but warmer temperatures will allow for greater and more rapid evapotranspiration, which could lead to drier conditions in some areas (particularly in midcontinent, midlatitude regions). Hydrologic studies suggest that river watersheds can be quite sensitive to even small climatic changes, particularly in arid and semiarid areas, where annual runoff tends to be highly variable. In river basins where snowmelt is important, both the annual total runoff and its seasonal distribution can be affected by changes in temperature and precipitation. Overall, climate change is expected to lead to significant changes in both high-flow and low-flow runoff extremes (42).

Soils, Nutrients, and Vegetation

Soil development and nutrient cycling rely on a dynamic interaction among rock, plants, fungi and microorganisms, and atmosphere. The development of soils depends in part on the rock that contributes sediments as it erodes and weathers, on the kinds of plants that grow on the soil, generating detritus of varying composition, and on the microorganisms associated with the plants that decompose the detritus into nutrients and organic matter. Nutrients, including carbon and nitrogen, are cycled in various forms through plants, soil, and the atmosphere. The type of soil that has developed may limit the kinds of plants that can easily take root and survive (which then provide habitat for particular animal species that affect nutrient turnover from plants). The presence of vegetation further affects the soil by anchoring it, thus preventing erosion.

Both temperature and moisture affect the type of vegetation that grows, the amount of detritus produced, and the rate at which litter decomposes and releases nutrients that can then be used by other plants, animals, and microorganisms. With intermediate levels of moisture, increased temperatures accelerate decomposition. This may free more nutrients in the short term, potentially boosting productivity. However, faster decomposition could also release more carbon (in the form of CO_2) from the soil, particularly in the northern United States, where soils store a large share of the global carbon, thus amplifying the greenhouse effect. Furthermore, as described in the earlier section on $C0_2$, increased concentrations of atmospheric $C0_2$ will likely lead to changes in the composition and structure of plant leaves. The ratio of carbon to nitrogen may increase, which may actually slow the rate at which these leaves decompose and release minerals (see box 2-D). Changes in precipitation and runoff will also affect whether nutrients are maintained or lost more quickly from soils. More-frequent or more-severe storms could cause more erosion and soil loss in areas where land use is intensive or where vegetation has declined because of altered climate conditions (19, 42, 64).

The overall effects of climate change on soils are difficult to calculate because of the many complex and interacting processes that contribute to soil development. Regardless of the long-term change in soils, in the shorter term, soils may play an important role in vegetation changes. As temperatures warm the suitable ranges or climate conditions for many plant species may expand northward. However, soils at the northern edge of the United States and into central Canada tend to be thinner and less fertile than those in the

Midwest, which may make adaptation difficult for some species. In agricultural systems, any lack of nutrients in the soils can be compensated for by adding fertilizers, although there may be environmental costs associated with this (see vol. 1, ch. 6).

Sea Level, *Oceans, and* Coastal Ecosystems

The many interconnected physical changes in oceans and coasts will affect marine ecosystems in numerous ways (see box 2-C). Wave patterns in certain areas could be altered as a result of changes in regional climate, which could affect the stability of coastal areas.

Coral-building organisms thrive at a rather narrow range of water temperatures and depths. Although these organisms build reefs at a rate of up to 0.6 inches (1.5 cm) per year, fast enough to keep up with predicted sea level rise, other factors such as storms and warmer water temperatures could interfere with their growth and, in some cases, could kill the organisms, Loss of coral reefs would change the wave and water patterns near the coast and could allow for increased coastal erosion. Likewise, mangrove trees along many tropical coasts play an important role in shore stabilization. Sea level rise could inundate some mangrove swamps. As these trees die, the coast would be left vulnerable to erosion. In addition, the potential elimination of salt marshes and seagrass beds could have serious effects on marine organisms. However, wetlands may migrate landward at a rate dictated by the landward slope and sea level rise. In any case, the physical and biological changes along oceans and coasts could interact to amplify the effects of climate change (see vol. 1, ch. 4).

WHICH NATURAL RESOURCES ARE MOST VULNERABLE TO CLIMATE CHANGE?

Although regional predictions of the natural resources most at risk from climate change cannot be made based on existing knowledge, certain characteristics may put some parts of a natural resource system at greater risk than others. For example, ecosystems with limited options for adaptability-such as alpine ecosystems, old-growth forests, fragmented habitats, and areas already under stress-may be particularly vulnerable to changes in climate (42) (see vol. 2, ch. 5). How ecosystems will fare under climate change also depends on other factors that influence soil and water chemistry, including land use, air pollution, and water use (21). A1though systems at the edges of their ranges and those already stressed may be at the greatest risk from climate change, some systems that now appear healthy could also suffer.

Natural ecosystems may be more vulnerable to climate change than managed ones. Furthermore, natural or less managed ecosystems may be affected not only by changes in climate, but by further stresses resulting from human responses to those changes, such as increased irrigation, diversion of water from streams, and expanded tillage or grazing (see vol. 2, chs. 4 and 5). On the other hand, poor management responses in forestry and agriculture, such as planting species that are not well-adapted or maintaining g stands at high densities, could make some managed areas vulnerable as well (see vol. 1, ch. 6, and vol. 2, ch. 6). Vulnerability to climate change will certainly vary widely, and predictions about how systems will respond to climate change are difficult to make.

Changes in soil moisture may be among the best indicators that a natural resource system is becoming stressed. Figures 2-6 and 2-7 illustrate areas of the United States that may face changes in soil moisture under the climate change scenarios projected by GCMS. The extent to which these changes in soil moisture will affect areas of significant natural cover (34) is presented in figure 2-13. The figure shows the percent of area in each land class that is becoming effectively wetter (measured above the zero axis) or drier (below the zero axis). The GFDL scenario produces dramatic effects, with the majority of all existing ecosystems except tundra and deserts

Natural disturbances, such as the Yellowstone fires, create openings in forested areas where grasses and wildflowers can flourish. This provides new food sources for elk and other wildlife, Fires also promote recycling of nutrients, which enriches the soil.

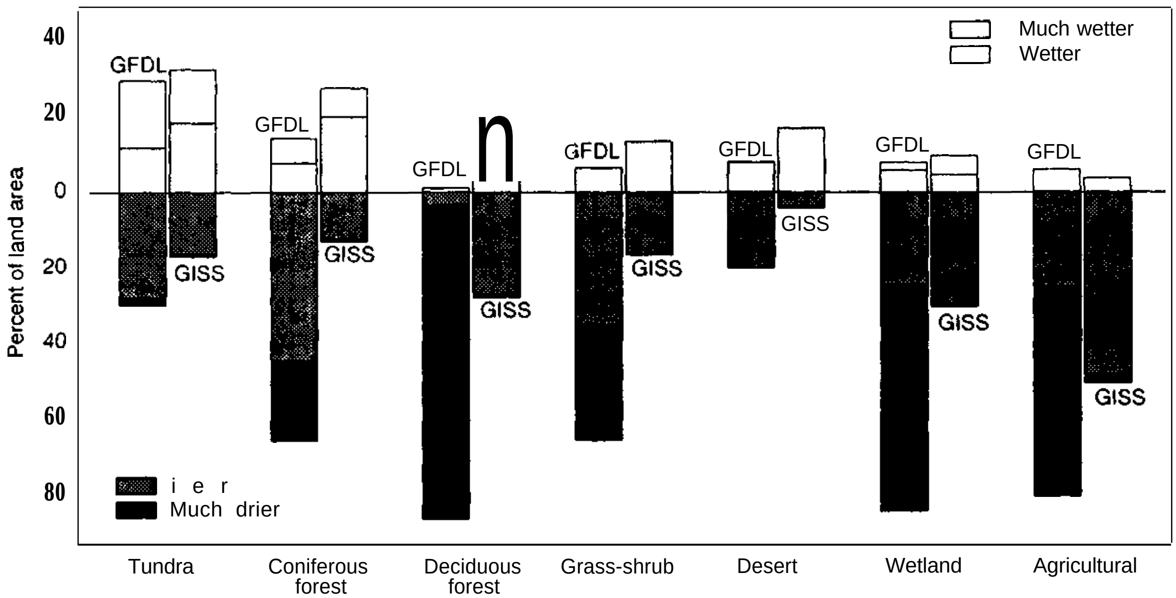
moving toward drier climatic regimes. Almost 80 percent of agricultural lands of the United States face drying under the GFDL, scenario. The GISS scenario produces a mix of wetting and drying in areas of natural cover, with the exception of some noticeable drying in the wetlands. Agricultural lands (the midwestern corn belt and California) are more effected, with over 40 percent of the agricultural lands showing some drying under the GISS scenario.

Natural resource systems could change in any number of ways in response to a changing climate, but not all changes damage things that humans value. For example, a gradual shift in the boundaries of a wetland would probably not be considered a damage unless this results in a reduction of the habitat, flood control, water filtering, or recreational services offered by that wetland. Similarly, an increase in tree mortality may be of no concern in a forest valued as wildlife habitat rather than as a source of timber supply.

The degree of human intervention may also influence the vulnerability of natural resource systems to climate change. Depending on how natural systems are valued, they may be managed along a spectrum from active to passive management regimes. Because intensively managed systems are considered valuable, and because people are already exerting effort and expense to keep them productive, use of additional measures to respond to a changing climate is likely. On the other hand, wilderness areas are essentially unmanaged--but highly valued precisely because of ‘this lack of management. Active intervention to protect these areas seems unlikely (see vol. 2, ch. 5), but there may be little loss of value from any but the most extreme effects of climate change on these natural areas. Thus, climate impacts on natural resource systems and the need for taking precautionary actions in preparation for climate changes cannot be evaluated without also considering how people value and manage these resources. These are the issues considered in subsequent chapters that investigate the effects of and possible responses to climate change in individual natural resource sectors: coastal systems, water resources, agriculture, wetlands, preserves, and forests.

The Intergovernmental Panel on Climate Change, the National Academy of Sciences, and the U.S. Environmental Protection Agency have all conducted assessments of the potential impacts of climate change (see box 2-F). Their reviews describe numerous impacts of climate change on U.S. natural resource systems, which laid the foundation for this report. Subsequent chapters will summarize some of the predictions made by these reports for individual natural resources, then explore in greater detail the

Figure 2-13-Soil-Moisture Changes Under the GFDL and GISS Climate Change Scenarios, by Land-Use and Cover Type



NOTE: Bars above the zero axis represent the percent of land-use area predicted to become wetter bare below the axis chow the percent of land area becoming drier. Drying or wetting is calculated from the change In the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET). No change is reported If the index changed (up or down) by lees than 0.025; wetter= 0.25 to 0.05; much wetter= > .05; drier= -0.25 to -.05; much drier. <-0.05. GFDL-Geophysical Fluid Dynamics Laboratory, GISS=Goddard Instltute for Space Studies.

SOURCE: P.N. Halpin, "Ecosystems at Risk to Potential Climate Change,"contractor report prepared for the Office of Technology Assessment, June 1993.

vulnerability and adaptability of the various resources and the potential management strategies and policies that might assist adaptation.

CHAPTER 2 REFERENCES

1. Albrecht, B.A., "The Effect of Uncertainty in the Representation of Cloud Processes in Climate Models on Climate Change Prediction," in: *Effects of Scientific Uncertainties on the Accuracy of Global Climate Change Predictions: A Survey of Recent Literature,* M.E. Fernau and D.W. South (eds.), U.S. Department of Energy (DOE) Internal Report, Argonne National Laboratory, Environmental Assessment and Information Sciences Division, Technology and Environmental Policy Section (Argonne, IL: DOE, October 1991).
2. Arp, W.J., and B.G. Drake, "Increased Photosynthetic Capacity of *Scirpus olneyi* After 4 Years of Exposure to Elevated CO_2," *Plant, Cell, and Environment,* vol. 14, No. 9, 1991, pp. 1003-6.
3. Assel, R.A., "Impact of Global Warming on Great Lakes Ice Cycles," in: *The Potential Effects of Global Climate Change on the United States, Appendix A: Water Resources, EI?A-23@OS-89-050,* J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 1989).
4. Ausubel, J.H., "Does Climate Still Matter?" Nature, vol. 350, 1991, pp. 649-52.
5. Ausubel, J.H., "A Second Look at the Impacts of Climate Change," *American Scientist, vol. 79,* 1991, pp. 210-21.
6. Balling, R.C., Jr., "The Global Temperature Data," Research & *Exploration, vol. 9, No. 2, Spring 1993, pp. 201-07.*
7. Bazzaz, F.A., "The Response of Natural Ecosystem to the Rising Global CO_2 Levels," Annual *Review of Ecology and Systematics,* vol. 21, 1990, pp. 167-%.
8. Bazzaz, PA., and ED. Fajer, "Plant Life in a CO_2-Rich Wor14° *Scientific American,* vol. 226, No.1, January 1992, pp. 68-74.
9. Bean, M.J., "Waterfowl and Climate Change: A Glimpse into the Twenty-First Century," Orion Nature Quarterly, Spring 1989, pp. 22-27.

Box 2-F–Major Assessments of Climate Change Impacts

Three major assessments by national and international organizations have addressed the potential impacts of climate change: the U.S. Environmental Protection Agency's (EPA's) 1989 report, The Potential *Effects of Climate Change (94),* the three-volume climate change series issued by the Intergovernmental Panel on Climate Change in 1990 *(42, 43, 44,* and the 1992 supplement (45)), and a 1991 report by the National Academy of Sciences, Policy */mplications of Greenhouse Warming (22),* and its 1992 supplement. These reports focus on different aspects of climate change. Taken together, they lay the foundations for OTA's assessment of the adaptability and vulnerability of systems to climate change, and their findings are cited throughout this chapter.[1]

The EPA Report—In 1987, Congress requested that EPA study "the potential health and environmental effects of climate change including, but not. . . limited to, the potential impacts on agriculture, forests, wetlands, human health, rivers, lakes, estuaries, as well as societal impacts." To respond, EPA conducted a massive 2-year effort, hiring more than a hundred contractors to model potential effects on each system, and contracting out several regional case studies to integrate how all impacts might interact in different regions. The results were synthesized in a 400-page report accompanied by 11 appendixes of contractor papers.

EPA used regional predictions of temperature and precipitation generated by four major general circulation models GCMs to examine the sensitivities of managed and unmanaged systems and to evaluate regional effects. The climate predictions were distributed to contractors, who then incorporated the results into their own models for crop growth, forest productivity, farm-level decisionmaking, etc., to predict the potential effects on particular systems and in particular regions.

EPA found that unmanaged systems such as coastal wetlands, parks, and forests "maybe unable to adapt quickly to rapid warming." Effects could include a reduced range for many tree species, changes in forest composition, a decline in cold-water fish and shellfish (although some warm-water species could benefit), an increase in species extinction, loss of coastal wetlands, and an increase in salinization of estuaries. Such impacts could begin in 30 to 80 years. Climate changes may heighten the effects of other stresses (such as pollution, increased radiation accompanying stratospheric ozone depletion, pests and pathogens, and fire). For example, climate-induced stress may make large regions of forests more susceptible to other stresses, such as fire, pests, disease outbreaks, wind damage, and air pollution. Changes in forest species and productivity could lead to secondary effects such as increased soil runoff and erosion, reduced aquifer recharge, reduced biodiversity, and changes in wildlife habitat and recreational opportunities. Species extinctions could increase (and biological diversity could decline), especially in areas where roads, agriculture, and urban development block or restrict migration pathways or habitat, and in areas that harbor heat-or drought-sensitive species. Some forested land could become grassland. As communities and ecosystems are displaced by climate change, it may be necessary to expand scientific knowledge on the practice of ecosystem restoration, so that communities can be rebuilt in degraded sites or relocated to new areas where they have not existed in the past (94) (see also vol. 2, boxes 4-A and 5-M).

Overall, EPA found that managed systems such as water resources and agriculture are more capable than natural systems of withstanding climate change. However, problems may still arise as humans attempt to adapt to the changes to these systems brought about by climate change. Agricultural yields might be reduced, but productivity could shift northward so that overall production could probably meet domestic needs, with some possible reductions in exports. Farmers might have to change their practices, such as beginning or increasing irrigation, which might increase conflicts over water use. If climate change leads to reduced stream flows, water quality may suffer because less water will be available for diluting or flushing pollutants and dissipating heat; these

[1] Ail three reports were based on the assumption that there would be no major changes in climate variability.

Changes could affect fish and wildlife populations. The effects on agriculture might vary considerably over regions, with declines, for example, in crop acreage in t he Great Plains potentially offset by increased acreage in the Great Lakes States.

Quality of life may not suffer much in areas where, for example, forests shift from one species to another, and where the shifts are gradual; however, in areas where forests die altogether (such as may occur in some parts of California), people would face severe environmental and land-use effects. Recreation relies on relatively healthy forests; rapid changes that caused stressed or declining forests would Iikely reduce recreational opportunities and demand.

The IPCC Report—The Intergovernmental Panel on Climate Change (IPCC) is an international group of hundreds of scientists from more than 50 countries established in 1988 by the World Meteorological Organization and the United Nations Environment Program. The IPCC setup three working groups: Working Group I to assess the scientific basis for how human activities affect the climate; Working Group II to study the potential impacts of climate change worldwide; and Working Group Ill to formulate possible policy responses. The results were Published in the three-volume Climate Change report in 1990 (The *IPCC Scientific Assessmemt, The IPCC Impacts Assessment* and The /PCC Response *Strategies).* The working groups continue to meet, and issue occasional updates to the 1990 reports.

The scientific assessment predicted that under a ''business-as-usual" scenario (characterized by continued reliance on coal-intensive energy sources and only modest efficiency increases), the global average temperature would increase at a rate of 0.5°F (0.3 °C) per decade, with a likely increaseof2'F (1 °C) over current levels by 2025 and 5.4 °F (3 °C) before the end of the next century. The impact assessment used this business-as-usual prediction for increasing temperature (with accompanying estimates that equivalent atmospheric CO_2 concentrations would double by 2025 to 2050 and sea level would rise about 1 foot (0.3 meter) by 2030) to predict potential impacts on systems including natural terrestrial ecosystems, agriculture, and forestry.

IPCC suggested that climate change could shift climatic zones several hundred miles toward the poles over the next 50 years, requiring natural terrestrial ecosystems to either migrate or adapt to a new climate regime. The rate of change will determine the degree of impacts: some species might be able to keep up with change, but some could become extinct, thus reducing global biodiversity. Ecosystems are unlikely to move as units, but will develop new structures as species abundance and distribution are altered. Most at risk are systems with limited options for adaptability (montane, alpine, and polar areas, island and coastal communities, remnant vegetation, heritage sites or reserves, and areas already under stress). Sea level rise and ocean warming will affect fisheries, potentially reducing habitat for several commercially important species. Coastal wetlands may be inundated by rising seas and forced to migrate inward, though in many areas, this may not be possible. Inland wetland areas may come under increased pressure for agricultural use. As for managed systems, forests may become more susceptible to parasites, and losses from fires will increase. It is urclear whether global agricultural productivity would increase or decrease overall, but many regions are likely to experience shifts or losses in production (for example, a decline in cereal and horticultural production in the southern United States), which will alter trade patterns. Impacts will differ considerably from region to region, as will the socioeconomic effects. Water availability will likely increase in some areas and decrease in others, but regional details are not yet known. There may also be a change in drought risk which could seriously affect agriculture at both the regional and global levels.

The NAS Report—The National Academy of Sciences (NAS) convened three different scientific panels to conduct preliminary analyses of climate change effects, mitigation strategies, and adaptation strategies. Each panel drafted a report that described their analyses and conclusions. A fourth "synthesis" panel drew on the work of the other three panels to formulate a policy report which was published in April 1991.

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2 The Cumulative warming effect of all greenhouse gases is equivalent to a doubled $C0_2$ concentration.

(Continued on next page)

Box 2-F-Major Assessments of Climate Change Impacts-(Continued)

The NAS panels assumed greenhouse warming In the range of 2 to 9°F(1 to 5°C), but did not give a specific time frame of reference. Based on this scenario, NAS classified natural resource systems and human activities into one of three categories: low sensitivity to climate change within the given range; sensitive but adaptable at a cost; and sensitive with questionable ability to adjust or adapt. NAS concluded that built systems generally fit into the first or second categories, and managed crop or timber lands fit into the second.

Water resources are quite sensitive to climate because runoff is the "small difference between the larger quantities of precipitation and evaporation," and runoff fluctuates relatively more" than either precipitation or evaporation. Changes in runoff will have adverse impacts only when water supply no longer matches water demand for use and consumption. In the United States, water supply and demand are now closely matched in the Great Basin, Missouri, and California water regions, so these areas maybe particularly vulnerable to decreases in precipitation (and conversely, they would reap large benefits should precipitation increase). Activities such as irrigation are also vulnerable to decreased precipitation because irrigation is most common in areas where precipitation is already light and evaporation is high. Unless climate changes quickly relative to demographic changes that affect water demand, however, the NAS report concludes, "the overall impact of climate change is unlikely to be substantially more serious than that of the vagaries of the current climate" {21).

In contast, NAS suggested that unmanaged ecosystems—the "natural landscape" and marine ecosystems-respond relatively slowly to climate change and that their ability to adapt is questionable and "problematic."

SOURCE : Office of Technology Assessment, 1993.

10. Blumberg, A.F., and D.M. Di Toro, "The Effects of Climate Warming on Lake Erie Water Quality," in: *The Potential Effects of Global Climate Change on the United States, Appendix A: Water Resources,* EPA-230-05-89-050, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 1989).

11. Botkin, D.B., and R.A. Nisbet, "projecting the Effects of Climate Change on Biological Diversity in Forests," in: G1oM *Warming and Biological Diversity,* R.L. Peters and T.E. Lovejoy (eds.) (New Haven, CT: Yale University Press, 1992).

12. Botkin, D.B., R.A. Nisbet, and T.E. Reynales, "Effects of Climate Change of Forests of the Great Lakes States," in: *The Potential Effects of Global Climate Change on the United States, Appendix D: Forests,* EPA-230-95-89-054, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 1989).

13. Brady, N.C., *The Nature and Properties of Soils, 9th Ed. (New York, NY:* MacMillan Publishing, 1984), 750 pp.

14. Brewer, R., *The Science of Ecology (Philadelphia* Saunders college Publishing, 1988).

15. Broecker, W. S., "Unpleasant Surprises in the Greenhouse?" *Nature,* vol. *328, 1987, pp. 123-26.*

16. Browne, M.W., "Report Says Carbon Dioxide Rise May Hurt Plants," New *York Times,* Sept. 18,1992, p. A14.

17. Bums, R.M., and B.H. Honkala, "Silvics of North American Conifers," VOL *l, Agriculture Handbook 654* (Washington, DC: U.S. Department of Agriculture, Forest Service, 1990).

18. Chambers, J.R., "U.S. Coastal Habitat Degradation and Fishery Declines " in: *Transactions of the North American Wildlife and Natural resources Conference* (Washington, *DC: The* Wildlife --- Institute, in press).

19. Clark, J.S., C.D. Reid, and G. Derda, *Sensitivity of Major North American Terrestrial Biomes* to *Global Change,* draft *report* prepared for the Electric Power Research Institute, 1992,

20. Clark, W.C., "Scale Relationships in the Interactions of Climate, Ecosystems, and Societies," in: *Forecasting in the Social and Natural Sciences, KC. Land and* S.H. Schneider (eds.) (Boston, MA: D. Reidel Publishing Co., 1987), pp. 337-78.

21. Committee on Science, Engineering, and Public policy, Panel on Policy Implications of Greenhouse Warming, National Academy of Sciences, National Academy of Engineering, Institute of Medicine, *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base* (Wash-@@x% *DC:* National Academy Press, 1992).

22. Cooper, C.F., "Sensitivities of Western U.S. Ecosystems to Climate Change," contractor report prepared for the Office of Technology Assessment, August 1992.

23. Cox, G.W., "Review of Draft Report on Vulnerabilities of Western U.S. Ecosystems to climate Change: Biodiversity and Wildlife Issues," draft contractor paper prepared for Office of Technology Assessment, July 1992.

24. Croley, T.E., I?, and H.C. Hartmann, "Effects of Climate Changes on the Laurentian Great Lakes Levels," in: *The Potential Effects of Global Climate Change on The United States, Appendix A:* Water Resources, EPA-230-05-89-050, J.B. Smith and D. Tirpak (eds.) (Washington DC: U.S. Environmental Protection Agency, June 1989).

25. Davis, O.K., "Ancient Analogs for Greenhouse Warming of Central California," in: *The Potential Effects of Global Climate Change on the United States, Appendix D: Forests, EPA-230-95-89-054,* J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 1989).

26. Dawson, W.R., "Physiological Responses of Animals to Higher Temperatures," in: *Global Warming and Biological Diversity,* R.L. Peters and T.E. Lovejoy (eds.) (New Haven, CT: Yale university Press, 1992).

27. Drake, B.G., "Effect of Elevated CO_2 on Chesapeake Bay Wetlands," *Responses of Vegetation to Carbon Dioxide,* in: *Ecosystem and Whole Plant Responses,* U.S. Department of Energy (DOE), mice of Energy Research, Carbon Dioxide Research Division (Washington DC: DOE, April-November 1988).

28. Drake, B.G., Research Scientist, Smithsonian Environmental Research Center, testimony before the Senate Committee on Commerce, Science, and Transportation Hearing on Global Change Research: Global Warming and the Biosphere, Apr. 9, 1992.

29. Emanuel, W.R., H-H. Shugart, and M.P. Stevenson, "Climatic Change and the Broad-Scale Distribution of Terrestrial Ecosystern complexes," *Climate Change, vol. 7, 1985,* pp. 29-43.

30. Frederick, K., and P. Gleik, "Water Resources and Climate Change," m: *Greenhouse Warming: Abatement and Adaptation, N.* Rosenberg, W. Easterling, P. Crosson, and J. Darmstadter (eds.) (Washington, DC: Resources for the Future, 1988).

31. Glantz, MH., "The Use of Analogies in Forecasting Ecological and Societal Responses to Global Warming, "Environment, vol. *33, December* 1991, pp. 11-15,27-33.

32. Grulke, N.E., G.H. Riechers, W.C. Oechel, U. Hjelm, and C. Jaeger, "Carbon Balance in Tussock Tundra Under Ambient and Elevated Atmospheric CO_2," *Oecologia,* vol. 83, 1990, pp. *485-494.*

33. Hains, D.K., and C-F. Hains, "Impacts of Global Warming on Runoff in the Upper Chattahoochee River Basin,' in: *The Potential Effects of Global Climate Change* on the *United States, AppendixA: Water Resources,* EPA-230-05-89-050, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 1989).

34. Halpin, P.N., "Ecosystems at Risk to Potential Climate Change," contractor report prepared for the Office of Technology, June 1993.

35. Hammond, AL., "Ecosystem Analysis: Biome Approach to Environmental Science," *Science,* vol. 175, 1972, pp. 46-48.

36. Hansen, A.J., 'EA. Spies, F.J. Swanson, and J.L. Ohmann, "Conserving Biodiversity in Managed Forests," *Bioscience,* vol. 41, 1991, pp. 382-92.

37. Hansen, J., W. Rossow, and I. Fung, "Long-Term Monitoring of Global Climate Forcings and Feedbacks," in: *NASA Goddard Institute for Space Stud-es Conference Publication, New York,* 1992.

38. Heimann, M., "Modeling the Global Carbon Cycle," paper presented at& FM Demetra Meeting on climate Variability and Global Change, Chianciano Therme, Italy, Oct. 28-Nov. 3, 1991.

39. Holdridge, L.R., *Life Zone Ecology (San* Jose, Costa Rica: Tropical Science Center, 1%7).

40. Hopkins, A.D., *Bioclimatics: A Science of Life and Climate Relations,* U.S. Department of Agriculture (USDA) Miscellaneous publication 280 (Washington, DC: USDA, 1938).

41. Idso, S.B., "The Aerial Fertilization Effect of CO_2 and Its Implications for Global Carbon Cycling and Maximurn Greenhouse Warming, " *Bulletin of the Amen"can Meteorological Society,* vol. *72, No. 7,* July 1991, pp. %2-65.

42. Intergovernmental Panel on Climate Change (IPCC), World Meteorological Organization and United Nations Environment Program, Climate *Change: The IPCC Impacts Assessment, report* prepared for IPCC by Working Group II, WJ. McG. Tegart, G.W. Sheldon, and D.C. Griffith (eds.) (C-Australia: Australian Government publishing Service, 1990).

43. *Intergovernmental* Panel on Climate Change (WCC), World Meteorological Organiztion, and United Nations Environment Program, *Climate Change: The IPCC Response Strategies,* report prepared for IPCC by Working Group III, *1990.*

44. *Intergovernmental* Panel on Climate Change (IPCC), World Meteorological Organization and United Nations Environment Program, Climate *Change: The IPCC Scientific Assessment,* report prepared for IPCC by Working Group I, J.T. Houghton, GJ. Jenkins, and JJ. Ephraums (eds.) (Cambridge, England: Cambridge University Press, 1990).

45. Intergovernmental Panel on Climate Change, World Meteorological Organization, and United Nations Environment Program, *Climate* Change 1992: *The Supplementary Report to the IPCC Scientific Assessment, report* prepared for IPCC by Working Group I, J.T. Houghton, BA. Callander, and S-K. Varney (eds.) (Cambridge, England: Cambridge University Press, 1992).

46. Izrael, Y.A., and S.M. Semenov, "Ecological Standards Setting: Methodology and practical Issues: Problems of Ecological Monitoring and Ecosystems Modeling," Leningrad, *Gidrometeoizdat,* vol. 13 (in press).

47. Kareiva, P.M., J.G. Kingsolver, and R.B. Huey (eds.), *Biotic Interactions and Global Change* (Sunderland, MA: Sinauer Associates, Inc., 1993).

48. Karl, T.R., "Missing Pieces of the Puzzle," *Research & Exploration,* vol. *9, No. 2, Spring 1993,* pp. *234-49.*

49. Kellogg, W., and Z. Zhow, "Sensitivity of Soil Moisture to Doubling of Carbon Dioxide in Climate Model Experiments Part I: North America," *Journal of Climate,* vol. 1, No. *4,* April 1988.

50. Körner, D., and JA. Arnone, "Responses to Elevated Carbon Dioxide in Artificial Tropical Ecosystems, " Science, vol. 257, Sept. 18, 1992, pp. 1672-75.

51. Krutilla, J. V., "Conservation Reconsidered," *American Economic Review,* vol. 57, No. 4, September 1%7, pp. 777-86.

52. Lawren, B., ''NET LOSS,' *National Wildlife,* vol. 30, October/ November, 1992, pp. 47-50,52,
53. Lettenmaier, D.P., T.Y. Gan, and D.R. Dawdy, "Interpretation of Hydrologic Effects of Climate Change in the Sacrament O-sari Joaquin River Basin, California,'' in: *The Potential Effects of Global Climate Change on the United States, Appendix A: Water Resources,* EPA-230-05-89-050, J.B. Smith and D. Tirpak (eds.) (Washington DC: U.S. Environmental Protection Agency, June 1989).
54. Lindzen, R. S., "Some Coolness Concerning Global Warming," *Bulletin of the American Meteorological Society,* vol. 71,1990, pp. 288-290,
55. Lorius, C., J. Jouzel, D. Raynaud, J. Hansen, and H. Le Treut, "The Ice-Core Record: Climate Sensitivity and Future Greenhouse Warming," *Nature,* vol. 347, 1990, pp. 139-145.
56. Mahlman, J.D., ''Assessing Global Climate Change: When Will We Have Better Evidence?" in: *Climate Change and Energy Policy,* L. Rosen and R. Glasser (eds.), Los Alamos National Laboratory, LA-UR-92-502 (New York, NY: American Institute of Physics, 1992), pp. 17-31.
57. Manabe, S., and R.T. Wetherald, "Reduction in Summer Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide," *Science, vol.* 232, 1986, pp. 626-78.
58. Mattson, W.J., and R.A. Haak, ''The Role of Drought in Outbreaks of Plant-Eating Insects," *Bioscience,* vol. 37, No. 2, February 1987, pp. 11018.
59. McCormick, M.J., "Potential Climate Changes to the Lake Michigan Thermal Structure," in: *The Potential Effects of Global Climate Change on the United States, Appendix A: Water Resources,* EPA-230-05-89-050, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 1989).
60. Michaels, P.M., ''The Greenhouse Conflagration: Clinton/Gore and Global Warrning," lecture at The Cato Institute, Washington DC, Dec. 14, 1992.
61. Michaels, P.M., Sound and *Fury: The Science and Politics of Global Warming* (Washington, *DC: The* Cato Institute, 1992).
62. Miller, B.A., and W.G. Brock, "Potential Impacts of Climate Change on the Tennessee Valley Authority Reservoir System," in: *The Potential Effects of Global Climate Change on the United States, Appendix A: Water Resources, IlPA-230-05-89-050,* J.B. Smith and D, Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 1989).
63. Moreau, D.H., "It Will Be a Long Wait for Proof," paper *presented* at the Southeast Climate Symposium: Changing Climate and Water Resources, Charleston SC, Oct. 27-29, 1992,
64. National Science Foundation "Soil-Warming Experiments in Global Change Research,'' report of a workshop held in Woods Hole, MA, Sept. 27-28, 1991.
65. Norby, R.J., E.G. O'Neil, and RJ. Luxmoore, "Effects of Atmospheric $C0_2$ Enrichment on the Growth and Mineral Nutrition of *Quercus alba Seedlings in* Nutrient Poor Soil," *Plant Physiology,* vol. 82, 1986, pp. 83-89.
66. Oechel, W.C., "Effects of Anticipated Changes in Global Climate and Atmospheric CO_2 on Western Ecosystems: Chaparral and Associated Forest Ecosystems," draft contractor paper for Office of Technology Assessment, July 1992.
67. Oechel, W.C., ''Responses of Alaskan Biological and Social Systems to Climate Change: A Scenario," contractor paper prepared for Office of Technology Assessment, Jan. 11, 1993.
68. Oechel, W.C., and W.I). Billings, ''Effects of Global Change on the Carbon Balance of Arctic Plants and Ecosystems," in: Arctic *Ecosystems in a Changing Climate: An Ecophysiological Perspective,* F.S. Chapin III, RL. Jefferies, J. Svoboda, JR. Reynolds, and G.R. Shaves (eds.) (San Diego, CA: Academic Press, 1992), pp. 139-68.
69. Oechel, W.C., and BR. Strain, "Native Species Responses to Increased Carbon Dioxide Concentration,'' in: *Direct Effects of Increasing Carbon Dioxide on Vegetation,* DOE/ER-0238, B.R. Strain and J.D. Cure (eds.) (Washington, DC: U.S. Department of Energy, December 1985).
70. Overpeck, J.T., and PJ. Bartlein, "Assessing the Response of Vegetation to Future Climate Change: Ecological Response surfaces and Paleoecological Model Validation,'' in: *The Potential Effects of Global Climate Change on the United States, Appendix D: Forests, EPA-230-95-89-054,* J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 1989).
71. Parker, B.B., National Oceanic and Atmospheric Administration (NOAA), Ocean and Lake Levels Division, Office of Ocean and Earth Sciences, National Ocean Service, NOAA, "The Use of Long Historical Sea Level Records in the Study of Climate and Global Change," paper presented at Marine Technology Society '92, Washington DC, Oct. 19-21, 1992.
72. Perry, D.A., "Landscape Pattern and Forest pests," *Northwest Environmental Journal,* vol. *4, No. 213,* 1988.
73. Perry, *M., "The* Potential Effect of Climate Change on Agriculture and Land Use," *Advances in Ecological Research,* vol. 22, 1992, pp. 63-91.
74. Peters, RL., and J.D.S. Darling, ''The Greenhouse Effect and Nature Reserves," *Bioscience, December 1985, pp. 707-17.*
75. Pitt, D.E., "Data Leave Little Doubt That Fish Are in Peril ,“ *The New York Times,* Aug. 3, 1993, p. C4.
76. Ray, G.C., B.P. Hayden, A.J. Bulger, Jr., and M.G. McCormick-Ray, "Effects of Global Warming on the Biodiversity of Coastal-Marine Zones,'' in: Global *Warming and Biological Diversity,* RL Peters and T.E. Lovejoy (eds.) (New Haven, CT: Yale University Press, 1992), pp. 91-104.
77. Ray, G.C., M.G. McCormick-Ray, and F.M. Potter, Global *Climate Change and the Coastal Zone: Evaluation of Impacts on Man-ne Fisheries and Biodiversity of the U.S.,* contractor report prepared for the Office of Technology Assessment, February 1993,
78. Rin4 D., R Goldberg, J. Hansen, C. Rozenzwig, and R Ruedy, ''Potential Evapotranspiration and the Likelihood of Future Drought,'' *Journal of Geophysical Research,* vol. *95, No. D7,* June *20,* 1990, p. 10,001.
79. Rind, D., C. Rosenzweig, and R Goldberg, ''Modelling the Hydrological Cycle in Assessments of Climate Change," *Nature,* vol. 358, 1992, pp. 119-122.
80. Schneider, S., P. Gleick, and L. Mans, "Prospects for Climate Change," in: *Climate Change and U.S. Water Resources,* P. Waggoner (ed.) (New York: John Wiley and Sons, 1990), pp. 41-73.

81. Schneider, S.H., L. Mearns, and PH. Gleick, "Climate-Change Scenarios for Impact Assessment," in: *Global Warming and Biological Diversity*, R.L. Peters and T.E. Lovejoy (eds.) (New Haven, CT: Yale University Press, 1992), pp. 38-55.

82. Sheer, D.P., and D. Randall, "Methods for Evaluating the Potential Impacts of Global Climate Change: Case Studies of the State of California and Atlanta, Georgia," in: *The Potential Effects of Global Climate Change on the United States, Appendix A: Water Resources*, EPA-230-05-89-050, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 1989).

83. Smith, W.H., "United States Forest Response and Vulnerability to Climate Change," contractor report prepared for the Office of Technology Assessment, May 1992.

84. Spencer, R.W., and J.R. Christy, "Precise Monitoring of Global Temperature Trends from Satellites," *Science*, vol. 247, 1990, pp. 1558-62.

85. Titus, J.G., cd., *Greenhouse Effect, Sea LevelRise, and Coastal Wetlands, EPA-230-05-86-013* (Washington, *DC:* U.S. Environmental Protection Agency, July 1988).

86. Topping, J. C., Jr., and J.P. Bond, *The Potential Impact of Climate Change on Fisheries and Wildlife in North America*, report of the Climate Institute to the U.S. Environmental Protection Agency, May 1988.

87. Tracy, C.R., "Ecological Responses Animals to climate, " in: Global *Warming and Biological Diversity*, R.L. Peters and T.E. Lovejoy (eds.) (New Haven, CT: Yale University Press, 1992).

88. U.S. Congress, Office of Technology Assessment (OTA), *Changing by Degrees: Steps to Reduce Greenhouse Gases*, OTA-O-482 (Washington, DC: U.S. Government Printing Office, February 1991).

89. U.S. Congress, Office of Technology Assessment (OTA), *Forest Service Planning: Accommodating Uses, Producing Outputs, and Sustaining Ecosystems*, OTA-F-505 (Washington, *DC:* U.S. Government Printing Office, February 1992).

90. U.S. Congress, Mice of Technology Assessment (OTA), *Harmful Non-Indigenous Species in the United States* (Washington, DC: Government *Printing* mice, 1993).

91. U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS), Our *Living Oceans: The First Annual Report* on *the Status of the U.S. Living Marine Resources, NOAA* Technical Memo, NMFS-F/SPO-1, 1991.

92. U.S. Department of Energy (DOE), Argonne National Laboratory, Environmental Assessment and Information Sciences Division, Technology and Environmental Policy Section, *Effects of Scientific Uncertainties on the Accuracy of Global Climate Change Predictions: A Survey of Recent Literature*, U.S. DOE internal report, M.E. Fernau and D.W. South (eds.) (Argonne, IL: DOE, October 1991).

93. U.S. Department of Energy (DOE), Office of Energy Research, Office of Basic Energy Sciences, Carbon Dioxide Research Division, *Direct Effects of Increasing Carbon Dioxide on Vegetation*, DOE/ER-0238, B.R. Strain and J.D. Cure (eds.) (Washington, DC: U.S. DOE, December 1985),

94. Us. Environmental Protection Agency (EPA), *The Potential Effects of Global Climate Change on the United States, EPA-230-05-89-050*, J.B. Smith and D. Tirpak (eds.) (Washington DC: U.S. EPA, December 1989).

95. U.S. Environmental protection Agency (EPA), *The Potential Effects of Global* Climate *Change on the United* States, *Appendix A: Water Resources, EPA-23* 0-05-89-050, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. EPA, June 1989).

%. U.S. Environmental Protection Agency (EPA), *The Potential Effects of Global Climate Change on the United States, Appendix D: Forests*, EPA-230-95-89-054, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. EPA, June 1989).

97. Urban, D.L., and H.H. Shugart, "Forest Response to Climatic change: A Simulation Study for Southeastern Forests," in: *The Potential Effects Of Global Climate Change On The United States, Appendix D: Forests*, EPA-230-95-89-054, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 1989).

98. Warren, S-R., Coastal *Wetland Vulnerabilities to Climate Change*, contractor report prepared for Office of Technology Assessment, July 30, 1992.

99. Warrick, R.A., R Gifford, and M.L. Parry, "CO_2, Climatic Change and Agriculture," in: *The Greenhouse Effect, Climatic Change and Ecosystems*, B. Bolin et al. (eds.), SCOPE 29 (New York, NY: John Wiley and Sons, 1986).

100. Webb, T., III, "Past Changes m Vegetation and Climate: Lessons for the Future," in: Global *Warming and Biological Diversity*, R.L. Peters and T.E. Lovejoy (eds.) (New Haven, CT: Yale University Press, 1992), pp. 59-75.

101. Willard, D.E., and L.D. Kosmond, *A Watershed-Ecosystem Approach to Lund and Water Use Planning and Management, contractor* report *prepared* for the Office of Technology Assessment Aug. 28, 1992.

102. Willard, D.E., et al., *Wetland Vulnerabilities to Climate Change, contractor report prepared* for the Office of Technology Assessment, Aug. 18, 1992.

103. Williams, P.B., "The Impacts of Climate Change on the Salinity of San Francisco Bay," in: The *Potential Effects of Global Climate Change on the United States, Appendix A: Water Resources, EPA-230-05-89-050*, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 1989).

104. Woodman, J.N., and C.S. Furiness, "potential Effects of Climate Change on U.S. Forests: Case Studies of California and the Southeast," in: *The Potential Effects of Global Climate Change on the United States, Appendix D: Forests*, EPA-230-*95-89454*, J.B. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, June 1989).

105, Wyman, R.L., "Multiple Threats to Wildlife: Climate Change, Acid Precipitation, and Habitat Fragmentation," in: *Global Climate Change and Life on Earth*, R.L. Wyman (cd.) (New York, NY: Routledge, Chapman, & Hall, 1991), pp. 134-55.

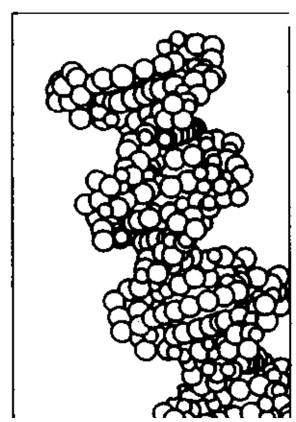
106. Zabinski, C., and M.B. Davis, "Hard Times Ahead for Great Lakes Forests: A Climate Threshold Model Predicts Responses to CO_2-Induced Climate Change," in: *The Potential Effects of Global Climate Change on the United States, Appendix D: Forests*, EPA-230-95-89-054, J.B. Smith and D. Tirpak (eds.) (Washington, DC: Us. Environmental Protection Agency, June 1989).

107. Ziska, L.H., B.G. Drake, and S. Chamberlain, "Long-Term Photosynthetic Response in Single Leaves of a C_3 and C_4 Salt *Marsh Species Grown at Elevated Atmospheric CO_2 in Situ*," *Oecologia*, vol. 83, 1990, pp. 469-72.

Global Change Research in the Federal Government 3

On October 13, 1992, the United States ratified the United Nations Framework Convention on Climate Change. The convention was one of the key accomplishments of the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992. Its declared goal is "stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system, ' and it calls for parties to return "individually or jointly to their 1990 levels of these anthropogenic emissions of carbon dioxide and other greenhouse gases not controlled by the Montreal Protocol" (46). Most of the 166 countries that signed the convention have pledged to do so by 2000 (on April 21, 1993, President Clinton made a commitment to reduce U.S. greenhouse gas emissions to 1990 levels by that year). The convention also requires all participating countries to prepare action plans detailing their strategy to mitigate climate change. The Biodiversity Convention, signed by most developing and industrialized countries at UNCED, calls for the development of strategies for global biodiversity conservation, and Agenda 21, the comprehensive action agenda to promote sustainable development adopted at UNCED, also calls for policies to minimize environmental degradation.

All these concerns about climate change, biodiversity, and sustainable development reflect a policy agenda that is inextricably linked to scientific research. "The relationships between scientific and technological advancement and government support are complex, and the stakes in these decisions are high, not just for scientists and engineers, but for society as a whole. Consequently, a better understanding of the process of articulating goals, both within and outside science, is vital" (3).



The Federal Government launched a multi-agency research effort in 1989 in response to the uncertainties and potential risks of climate change. Its purpose is to observe, understand, and predict global change (9). When the U.S. Global Change Research Program (USGCRP) was created as a Presidential Initiative in 1989, it did not have an explicit plan to link research to policy. Before codifying the program, Congress directed it to provide information useful to policy makers; however, Congress did not identify or mandate any mechanism to ensure this. When the program was first implemented, key questions of the scientists and policy makers were: Are humans significantly changing the climate, and can climate change be predicted? The program was intended to replace a crisis-driven, one-problem-at-a-time approach to environmental problems with a more systemic, proactive approach that recognizes that different environmental problems are linked by the very nature of the Earth system.[1] Although the program is scientifically well--grounded, it has become overwhelmingly a physical science program focused on basic Earth system processes that largely ignores the behavioral, economic, and ecological aspects of environmental problems. For example, understanding the role clouds play in climate change and the role of the ocean-land-atmosphere interface is now its highest priority.

Understanding the size and scope of USGCRP can be difficult, and the coordination challenges of such a large interagency program are formidable. Agency personnel committed to the program have made a commendable effort to ensure that the program functions smoothly. However, USGCRP is not a managed entity with one budget, nor does it have an authoritative body making decisions on projects. It is, rather, a loosely coordinated collection of several programs and budgets. Even this level of coordination is undermined at the legislative level, where the program, collected into a compilation of budgets by the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET), is splintered into several parts and never considered as a whole during the authorization, appropriation, and oversight processes.

The primary questions of policy makers have changed since 1989 in the wake of the world climate treaty and the publication of several key reports: the Intergovernmental Panel on Climate Change (IPCC) reports, the Environmental Protection Agency (EPA) reports on the potential effects of climate change and policy options, and the Committee on Science, Engineering and Public Policy (COSEPUP) report.[2] It is now generally accepted that unequivocal detection of the greenhouse effect requires another decade of measurements, and that rates of climate change and regional details about climate changes will not be available for at least that long (see ch. 2). Thus, questions being asked today have moved beyond the basic science issues of "observing, understanding and predicting' climate change to a second set of concerns: What can be done to mitigate or adapt to climate change? What are the climate effects of most concern? How can we manage natural and human systems wisely given an uncertain climate? Consequently, USGCRP'S mission statement and priorities are now too narrow to address questions such as how to minimize negative impacts of climate change.

The congressional committees requesting this study recognized that decisionmaking must continue in the face of uncertainty. They expressed the following concerns to the Office of Technology Assessment (OTA):

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[1] *The* Earth system is the sum of all interactions among living organisms and their biotic and abiotic environments.

[2] IPCC's *Scientific Assessment* (28), *Impacts Assessment* (26), *Response Strategies* (27), and *Supplementary Report to the IPCC Scientific Assessment* (29); EPA's *Policy Options for Stabilizing Global Climate* (52) and *The Potential Effects of Global Climate Change on the United States* (51); and COSEPUP's Panel on Policy Implications of Greenhouse Warming, National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base* (10).

- "We think it is prudent to begin--today—investigating how our research and develop ment programs should incorporate concerns about climatic uncertainty. "[3]
- "Do current U.S. R&D Programs focus on the right questions to provide information about effects on different systems, potential strategies for making systems more resilient in the face of climate change and adapting to such changes that may occur?'
- "What information can more research provide over various time frames to guide decisions about reducing greenhouse gas emissions, ameliorating effects of global climate change, and building resiliency into systems?'

Conducting research to answer some of these questions has been a low priority. Although the results of the program, as currently structured, will provide valuable information for predicting climate change, they will not necessarily contribute to the information needed by public and private decisionmakers to respond to global change. Three areas are particularly lacking: ecosystem-scale research, adaptation research (ecological, human, and economic), and integrated assessments (evaluation of all focused and contributing research results and their implication for public policy). Research can begin now on topics more closely related to policy decisions despite incomplete answers from the physical sciences. More research is needed on the impacts of climate change on natural and managed ecosystems and the resulting implications for land and water resource management, on how people adapt, and on why people resist change. Key projects for a USGCRP committed to policy-relevant research should also include gathering information about the relative importance of population size and expectations of quality-of-life improvements, the demand for goods and services (including clean water, agriculture and forestry products, and access to natural areas), and economic and institutional barriers to the dissemination and adoption of technological innovation. Some of the research in these areas will take decades and, if started now, may leave us much better prepared to respond to global change in the future.

Implicit in the current structure of USGCRP is that the initiation of a comprehensive adaptation research program must wait until predictions of climate change are reliable. However, there are several important reasons not to wait to initiate adaptation research. First, according to IPCC estimates, few reliable predictions of climate change on a regional scale will be available before the next 15 to 20 years. Although such regional information might help focus research on managed and natural systems in areas expected to experience the most change, research on ecosystems is a multidecade task (see vol. 2, chs. 4-6) and should begin now. Second, even though the effects of climate change on a regional level cannot currently be modeled accurately, general effects can be predicted, such as sea level rise. Adaptation research that addresses sea level rise and other effects of climate change need not wait for reliable predictions. Third, much adaptation research makes sense regardless of climate change. For example, restoration of wetlands addresses adaptation to climate change, but it also addresses the current depletion of wetlands due to other causes. Adaptation research can use historical records of societal, economic, and environmental impacts of environmental change combined with reasonable hypothetical scenarios for future environmental change (31).

Because policy makers and scientists have different educational and professional backgrounds, scientific research findings need to be translated

[3] House Committee on Science, Space, and Technology, letter to OTA, Sept. 27, 1991.

[4] Senate Committee on Environment and Public Works, letter to OTA, Oct. 4, 1991,

[5] Senate Committee on Commerce, Science, and Transporta tion, letter to OTA, Oct. 8, 1991.

into terms relevant to policy making and decisionmakiñ g. Regardless of the "completeness" of climate research, policy makers are making decisions now that affect global change and whether the Nation will mitigate and/or adapt to it. They also decide where to allocate scarce resources for research.

A recent National Research Council report, *Research to Protect, Restore, and Manage the Environment (37),* stated: "No matter how good the science, environmental problems cannot be solved without integrating the science with environmental policy. To accomplish that, integrative study is needed to bridge the multidisciplinary gaps and deal with the conflicting goals held by varied constituencies. Research is necessary but not sufficient to solve problems. " One way to improve the relevance of" research results for policy makers is through the use of integrated assessments. Integrated assessments are a mechanism for synthesizing all the research relevant to an identified problem and for presenting research results in policy-relevant language. Such assessments, if conducted by multidisciplinary teams on a regular basis, could help bring together and evaluate research results produced by USGCRP, which is now composed largely of isolated programs and projects.

Although assessments were not included in the original USGCRP program, they are included in a rudimentary form in the FY 1994 budget (8). However, there has been no fundamental change in the mission of USGCRP, which remains predominately focused on understanding climate change. As a result, different people draw different conclusions about what changes in research focus to expect from USGCRP. In addition, the quality of assessments is determined solely by the information fed into them and the backgrounds of those constructing the assessment homework. If ecological, economic, and sociological research continues to be neglected. the planned assessments will not be useful to policy makers (24). John Gibbons, assistant to the President for science and technology, testified recently that USGCRP needs to expand the scope of its research to include the impacts of climate change on natural and human environments and strategies for mitigating and adapting to climate change. He also recognized the need to improve the integration of research with policy making (20).

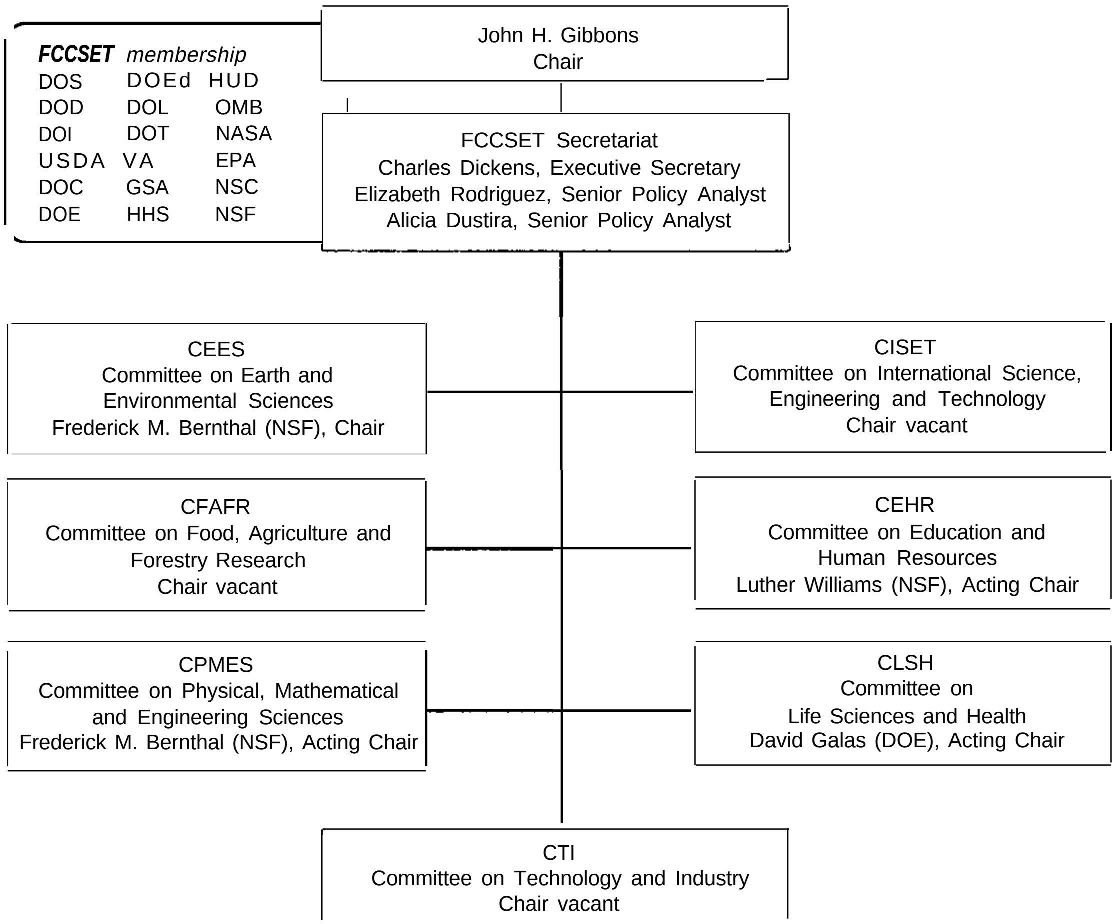
This chapter will examine the broad issues surrounding the Federal research effort to understand climate change-particularly within the context of the natural and managed systems discussed in chapters 4 through 6 of volumes 1 and 2. The options presented here, if implemented, could help commit the Federal Government to addressing areas of imbalance in USGCRP, the need for adaptation research, and the issues surrounding a national research program with an explicit science-policy interface. These program changes could benefit policy makers and decisionmakers by ensuring that USGCRP and other federally funded global change research supply the integrated information they need to make choices in the face of uncertainty about global change and its impacts.

THE U.S. GLOBAL CHANGE RESEARCH PROGRAM

Inception and Structure

Recognition that human activity could significantly alter the global environment grew during the 1970s and 1980s. Concerns focused particularly on the threat of climate change from increased emissions of greenhouse gases and the depletion of the ozone layer by chlorofluorocarbons (CFCS). In response to the potential risks of climate change and the uncertainties surrounding the science, the Federal Government launched a massive, multiagency research effort in 1989 "to observe, understand, and, ultimately, predict global changes and to determine the mechanisms influencing these changes" (9). In 1989, USGCRP was developed by the Committee on Earth Sciences (now the Committee on Earth and

Figure 3-1A--Organizational Chart for the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET)



NOTE: For definition of terms, eee figure 3-1 B, next page.

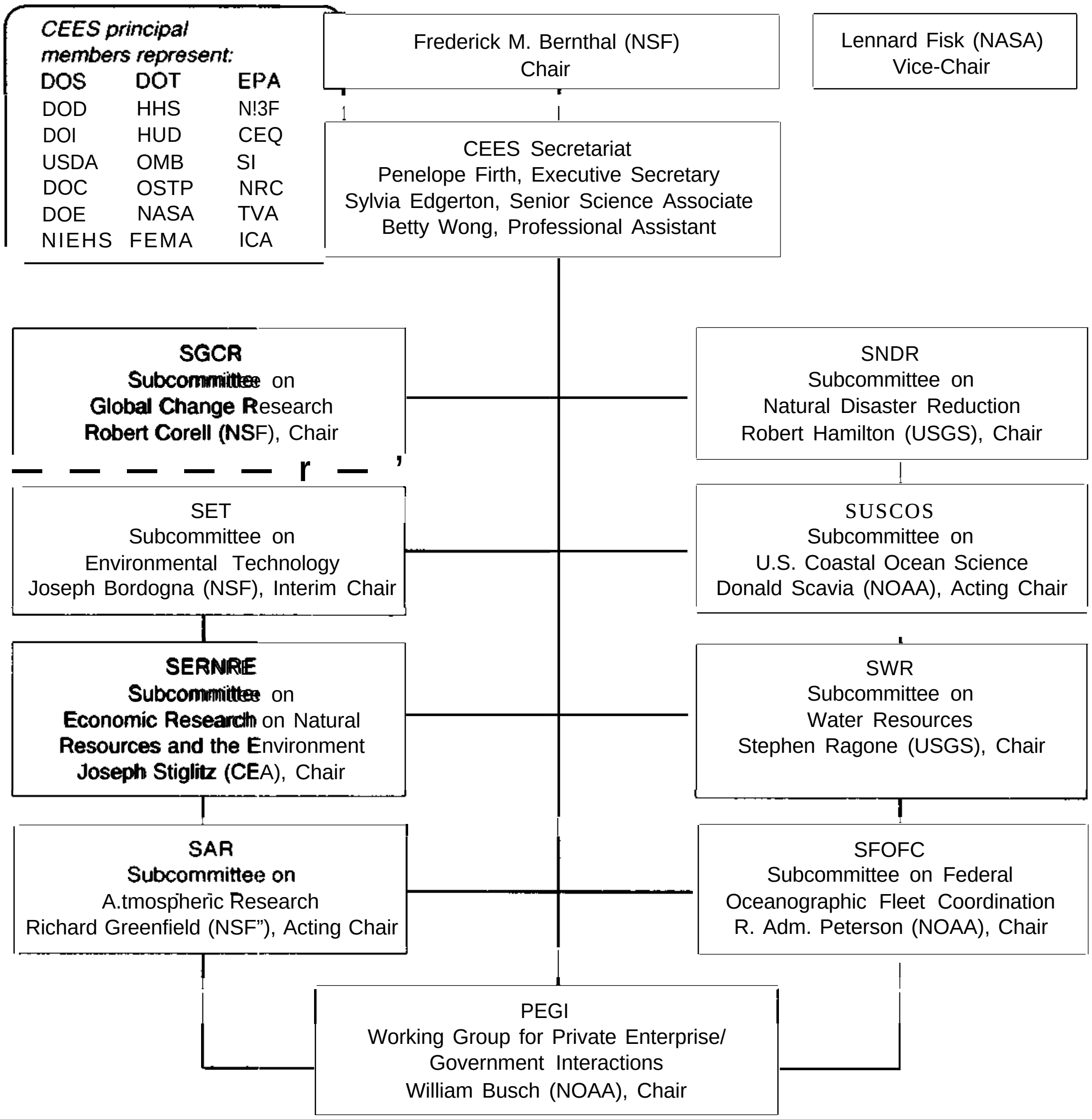
(Continued)

Environmental Sciences, CEES), an interagency group under FCCSET in the President's Office of Science and Technology Policy (OSTP) (see fig. 3-l). USGCRP became the first Presidential Initiative indicating that it was to be a high-priority program with strong administrative backing. In 1990, Congress passed the U.S. Global Change Research Act (P.L. 101-606), which codified USGCRP. In 1992, USGCRP became a National Research Program.[7] Between FY 1989 and FY 1993, the Government spent $3.7 billion on this effort. A new administration that asserts its commitment to taking action on climate change issues and a Congress with a large number of new members coincide with this 5-year benchmark and could change the direction and scope of the

6 Presidential Initiatives are programs of particular importance to the national interest. Aside from USGCRP, four other Presidential Initiatives exist: high-performancc computing and communication advanced materials and processing, biotechnology research, and mathematics and science education. The Administration uses FCCSET to coordinate interagency research in these areas.

7 FCCSET developed this category for continuing Presidential Initiatives that have reached maturity.

Figure 3-IB-Organizational Chart for the Committee on Earth and Environmental Sciences (CEES)



NOTE: DOS-Department of State; DOD-Department of Defense; DOI-Department of the Interior; USDA-U.S. Department of Agriculture; DOC-Department of Commerce; DOE-Department of Energy; DOEd-Department of Education; DOL-Department of Labor; DOT-Department of Transportation; VA. Department of Veterans Affairs; GSA-General Services Administation; HHS-Department of Health and Human Services; HUD-Department of Housing and Urban Development; OMB-Office of Management and Budget; NAS-National Aeronautics and Space Administration; EPA-Environmental Protection Agency; NSC-National Security Council; NSF-National Science Foundation; NIEHS-National Institute of Environmental and Health Sciences; OSTP-Office of Science Technology Policy; FEMA-Federal Emergency Management Agency; CEQ=Council on Environmental Quality; S1-Smithsonian Institution; NRC-National Research Council; TVA-Tennessee Valley Authority; ICA-Intelligenoe Community Affairs, CEA-Council of Economic Advisors; USGS-U.S. Geological Survey; NOAA-National Oceanic and Atmospheric Administration.

SOURCE: Committee on Earth and Environmental Sciences (CEES), Our Changing Planet.’ The FY 1994 *U.S. Global Change* Research Program (Washington, DC: CEES, 1993).

program for FY 1994. There is no official termination date for the program; however, program plans indicate that it will last at least 40 years (11).

Three ' 'activity streams, " or program elements, defined the USGCRP mission between its inception and FY 1994:

- Documentation and analysis of Earth system changes, which include observation—using both ground- and space-based observation systems-and data management;
- Process Research to enhance the understanding of the physical, geological, chemical, biological, and social processes that influence Earth system behavior; and
- Integrated Modeling and Prediction of Earth system processes.

Each of these priorities is represented by a working group under the Subcommittee on Global Change Research under CEES. The chair of the subcommittee along with the chair of each of the working groups make up the principal body responsible for the planning, development, coordination, and review of USGCRP (7). In FY 1994, a new activity stream, Assessment, was added.

USGCRP was originally envisioned as a complete global *change* research program, covering research on natural climate change, human-induced climate change, impacts of climate and land-use change on the Earth system, and impacts of human activity on ecosystem health. The program has evolved in parallel with the Intergovernmental Panel on Climate Change (IPCC) and has drawn heavily from the panel's work.[8] Consequently, the main focus of global change research under USGCRP has become climate change. Important global changes other than human-induced climate change, such as loss of biodiversity, changes in land use, and increases in industrial pollution, were determined to be beyond the scope of USGCRP and are addressed only to the extent that they interact with the climate system. This is reflected in the research priorities of the program's science elements.

To guide research, CEES identified and prioritized seven scientific research elements, or science elements.[9] In order of priority, the science elements are Climate and Hydrologic Systems, Biogeochemical Dynamics, Ecological Systems and Dynamics, Earth System History, Human Interactions, Solid Earth Processes, and Solar Influences (7). More-specific areas of research are prioritized under each of these seven research elements (see fig. 3-2). Several criteria, although not applied systematically, are used to evaluate projects under each research element, including: relevance and contribution to the overall goal of the program, scientific merit, ease or readiness of implementation, links to other agencies and international partners, cost, and agency approval.

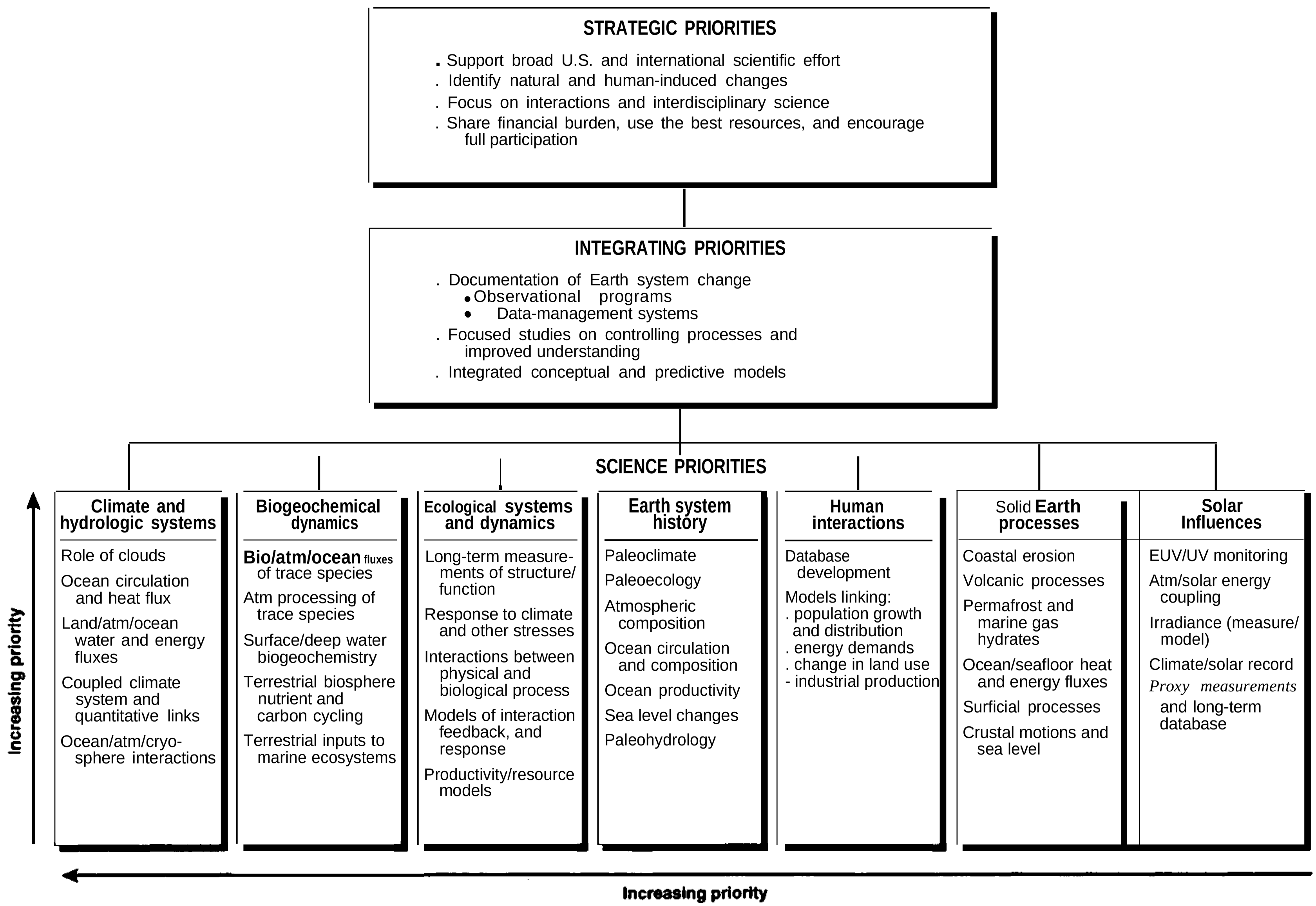
New Developments

In 1992, CEES began developing a management plan for the program that would include the addition of Assessment as a fourth activity stream along with Documentation, Process Research, and Integrated Modeling and Prediction (see fig. 3-3). The primary function of the Assessment working group is to ". . document the state of scientific knowledge and address the implications of the science of global change for national and intemational policy-making activities over abroad spectrum of global and regional environmental issues" (8). The group will also help coordinate the scientific assessments of global change with

[8] IPCC is an intergovernmental body sponsored jointly by the World Meteorological Organization and the United Nation's Environmental Programme. The group was set up in 1988 to assess the scientific understanding of natural and human-induced climate change, its impacts, and potential response strategies. IPCC is scheduled to produce another full assessment in 1995,

[9] CEES (formerly C'ES) works closely with and has drawn heavily on the ongoing activities of the National Academy of Sciences (NAS), the World Climate Research Program (WCRP) of the World Meteorological Organization the International Council of Scientific Unions (ICSU), the International Geosphere-Biosphere Program (IGBP), and IPCC in designing the structure of USGCRP and in identifying the program's key scientific issues and research priorities.

Figure 3-2-Priority Framework for USGCRP



NOTE: atm=atmosphere; EUV/UV=extreme ultraviolet/ultraviolet.

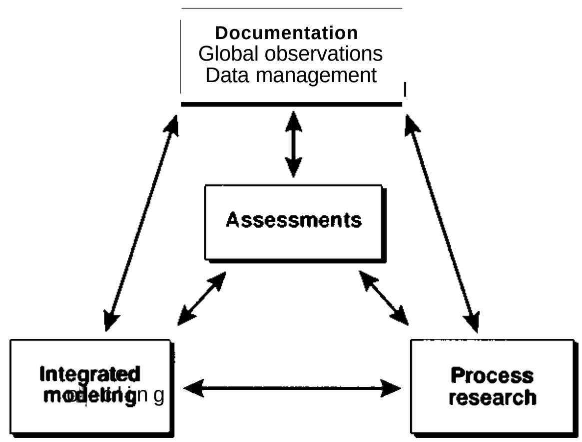
SOURCE: Committee on Earth and Environmental Sciences (CEES), *Our Changing Planet: The FY 1993 U.S. Global Change Research Program* (Washington, DC: CEES, 1992).

related assessments on environmental impacts, technologies for adaptation and mitigation, risk assessment, and policy-response strategies (12). Although the FY 1994 budget proposal reflects these changes, it is unclear how much money agencies will allocate for assessment and how the assessments will be structured. The FY 1994 budget does not show Assessment separately but, rather, embeds it within the other three activity streams. Comprehensive assessments cannot be carried out without expanding the ecological and socioeconomic aspects of the program and incorporating impacts research into it. The FY 1994 budget does not reflect any significant expansion in these areas.

Nonetheless, the Administration has expressed interest in significantly broadening the program to include studies of environmental and socioeconomic impacts and of mitigation and adaptation strategies. "The development of a successful assessment activity in the USGCRP will, I believe, go far toward demonstrating the Clinton-Gore administration's commitment not only to research but to effective action to manage this Nation's national and international environmental policy" (19). If this research materializes, it could then be integrated with research on Earth system processes to conduct integrated assessments. The expanded program should be reflected in the FY 1995 USGCRP budget.

To ensure progress in each of the activity streams, timetables and milestones have been included in each agency's USGCRP research program, although they have not appeared in any published document. These milestones, specified for both the near term (5 to 10 years) and the long term (10 to 30 years), "will guide program and budget development and serve as a critical element in evaluating program accomplishments and progress' (11). The Office of Management and Budget (OMB) could hold research programs to these targets only if the milestones are clearly stated and easily measured and, therefore, enforceable. Representative George Brown, chairman of the Committee on Science, Space, and

Figure 3-3-Functional Architecture of USGCRP



SOURCE: Committee on Earth and Environmental Sciences (CEES), Our *Changing Planet: The FY 1993 U.S. Global Change Research Program* (Washington, DC: CEES, 1992).

Technology, has suggested building performance guidelines into authorizing legislation as well as mandates that would redirect or terminate programs that do not make sufficient progress toward stated goals (2).

The Interface Between Policy and Science

Research programs intended to be relevant to management and policy making often fail because of fundamental tensions among researchers, resource managers, and decisionmakers. These tensions are created because of conflicts in the time horizons of each group, differences between priority- or goal-setting processes, and differences in the agendas of extramural research organimations (e.g., universities, industries, and independent laboratories), mission-oriented agencies, and Congress.

The timetable for governmental decisions is driven primarily by the annual budget cycle and an election cycle that ranges between 2 and 6 years. Not surprisingly, policy makers funding global change research often have a shorter time horizon for "answers" than do researchers. This disparity leads to tension between Government officials, who are required to formulate annual budgets and make immediate decisions, and the scientific community, whose long-term research is dependent on continuous and reliable funding. When the questions of policy makers are not answered in one or even a few years, it may become more difficult to sell a program as relevant to policy needs. Mission-oriented agencies are repeatedly deflected by the 'crisis-of-the-month' syndrome, which siphons resources away from long-term programs (37). The result maybe annual budget fluctuations and/or rapidly shifting priorities-both of which are detrimental to the development of a sound scientific program. A balance between continuity in priorities and finding and flexibility in project direction is essential (3).

Tension arises between extramural research organizations and the Federal Government because of different research agendas. Universities and independent laboratories judge their scientists to a large extent on their ability to raise funds for research. Adherence to management- and policy-relevant goals is not seen as important unless it leads to more Federal funding.

Many scientists believe that the science must be "complete" before policy conclusions can be made safely. Policy makers, on the other hand, cannot afford the luxury of complete information. Decisions about reauthorizing environmental legislation and natural resource planning and management will continue to be made based on the best available information, "[I]f policy is to be effectual, then we must make policy while we continue to investigate the physical and societal effects of global warming. But this means that policy will also enter the feedback loop, influencing societal responses and physical effects" (30). Science need not proceed in a sequential fashion. Research on the climate system need not be "complete" before research on the ecological effects of climate change is undertaken nor does research on the ecological effects of climate change need to be 'complete' before research on the societal impacts of and potential responses to climate change is initiated (45). If USGCRP is to address policy-relevant questions, a parallel ap preach to climate effects and response research is necessary.

In a narrow sense, USGCRP is policy-relevant if the most important policy concern is to gain a better understanding of Earth system processes in order to predict climate change. However, the major international assessments conducted by IPCC demonstrate that the key questions policy makers need to address move far beyond the narrow definition of "observe, document, and predict" global change, into the realm of issues related to adaptation and mitigation. As a result of focusing research funds on climate prediction, USGCRP is not addressing other key science issues or broad policy questions for the near term. For example, what plants and animals are sensitive to climate changes? How might biota and vegetation respond to changes in climate? What are the implications for forestry, agriculture, and natural areas? What mitigation strategies would slow climate change the most? How much would they cost? To whom? How might society respond to changes in climate and global ecosystems? What technologies should be developed? How will the effects of climate change interact with other global environmental changes? How important is climate change in the scheme of long-term environmental threats? How can natural resources be managed to minimize economic and ecological loss? These issues were largely excluded from USGCRP to keep it primarily driven by the earth sciences. Even if accurate regional climate predictions could be given today, land managers, planners, decisionmakers, and policy makers would not have all the information they need to guide their response (33). As originally envisioned in 1990, these issues were to be addressed under the CEES Working Group on Mitigation and Adaptation Research Strategies (MARS), which was abolished in 1992.

If USGCRP begins to address this broader set of questions, it will be moving closer to policy-relevant research. Some fear that a program driven by policy concerns will undermine or

Table 3-l—List of Departments and Agencies or Bureaus Involved in USGCRP Research

DOC	Department of Commerce	
	NOAA	National Oceanic and Atmospheric Administration
DOD	Department of Defense	
	CRREL	Cold Regions Research and Engineering Laboratory
	ONR	Office of Naval Research
DOE	Department of Energy	
	OHER	Office of Health and Environmental Research
DOI	Department of Interior	
	BIA	Bureau of Indian Affairs
	BLM	Bureau of Land Management
	BOM	Bureau of Mines
	BOR	Bureau of Reclamation
	FWS	Fish and Wildlife Service
	NPS	National Park Service
	OS	Office of the Secretary
	USGS	U.S. Geological Survey
EPA	Environmental Protection Agency	
	ORD	Office of Research and Development
HHS	Department of Health and Human Services	
	NIEHS	National Institute of Environmental Health Services
NASA	**National Aeronautics and Space Administration**	
	OSSA	**Office** of Space Science and Applications
NSF	National **Science Foundation**	
	BIO	Directorate for Biological Sciences
	GEO	Directorate for Geosciences
	SBE	Directorate for Social, Behavioral, and Economic Sciences
SI	Smithsonian Institution	
	IC	International Center
	NASM	National Air and Space Museum
	NMNH	National Museum of Natural History
	NZP	National Zoological Park
	SAO	Smithsonian Astrophysical Observatory
	SERC	Smithsonian Environmental Research Center
	STRI	Smithsonian Tropical Research Institute
TVA	Tennessee Valley Authority	
	RBO	River Basin Operations
USDA	Department of Agriculture	
	ARS	Agricultural Research Service
	CSRS	Cooperative State Research Service
	ERS	Economic Research Service
	FS	Forest Service
	SCS	Soil Conservation Service

SOURCE: Committee on Earth and Environmental Sciences (CEES), Our Changing Planet: The FY 1993 *U.S.* Global Change Research Program (Washington, DC: CEES, 1992).

change the direction of science. Others maintain that the second set of policy-related questions can be addressed adequately by research driven by the earth sciences. Maintaining the long-term policy relevance of scientific research under USGCRP will require a formal and iterative assessment link that simultaneously transfers scientific research results in policy-relevant language to decisionmakers and policy concerns to the research community.

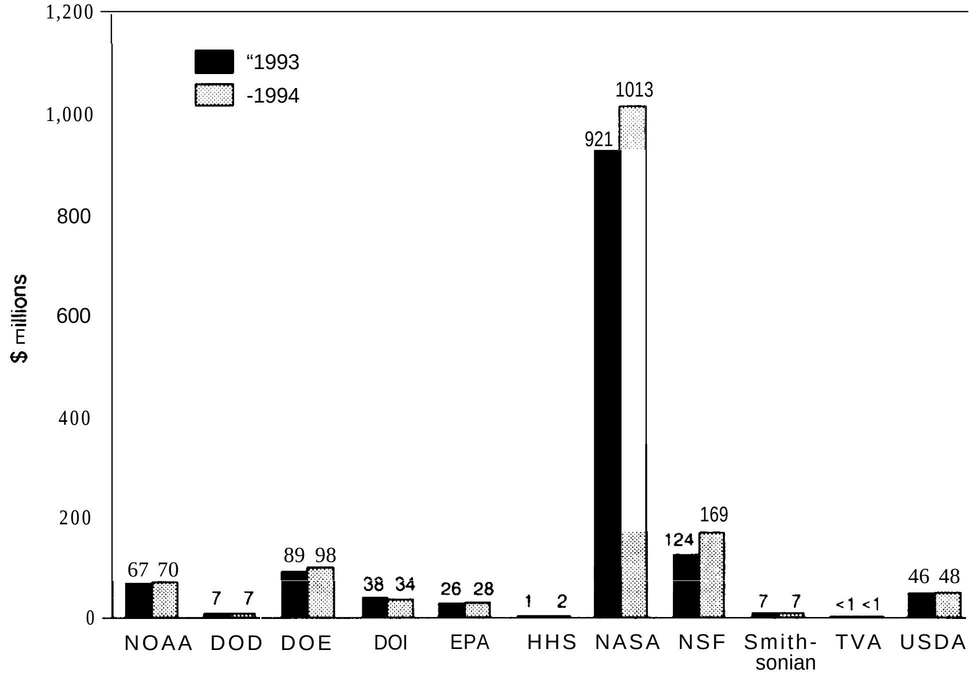
PRIORITIES AND BALANCE IN USGCRP

Budget

CEES designed USGCRP as a cohesive, integrated research program that would encompass the unique attributes of 11 Federal agencies, including 31 bureaus, but it did not assign a central management body (see table 3-l). The priority scheme set up by the three activity streams and the seven science elements is intended to guide budget decisions, and, to date, funding levels have followed these priority areas.

Since the program formally began in FY 1990, the USGCRP budget has grown from $660 million in its first year to $1.33 billion in FY 1993 (7, 9). The proposed budget for FY 1994 is $1.47 billion (8). The budget can be analyzed in terms of distribution across agencies, activity streams, and science elements (see figs. 3-4, 3-5, and 3-6). In FY 1993, projects funded by the National Aeronautics and Space Administration (NASA) comprised 69 percent of the program's budget ($921 million) while projects funded by the Department of the Interior (DOI), which contains most of the land-management agencies, comprised 3 percent of the program's budget ($38 million). For FY 1994, the requested budget for DOI'S global

Figure 3-4--U.S. Global Change Research Program Budget by Agency



NOTE: For definition of terms, see table 3-1. FY 1994 values are the requested, not the appropriated, amounts.

SOURCE: Committee on Earth and Environmental Sciences (CEES), Our Changing Planet: The FY 1994 *U.S. Global Change Research Program* (Washington, DC: CEES, 1993).

change research program decreased to 2.3 percent of the total.

Of the activity streams, Documentation, including observation and data management, received 45 percent of the budget ($595 million) in FY 1993. Earth Process Research for understanding climate change received 46 percent of the budget ($610 million), and Integrated Modeling and Prediction received 9 percent of the budget ($121 rnillion).[10]

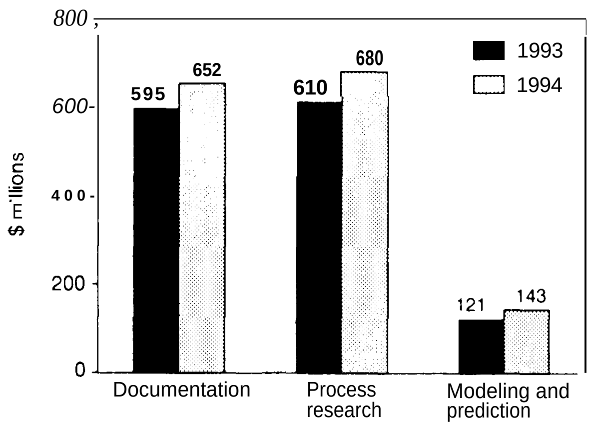
Although USGCRP programs include projects on almost every aspect of climate change, the bulk of the funds is focused on answering scientific questions related to understanding the physics and chemistry underlying climate systems. Research on Climate and Hydrologic Systems and Biogeochemical Dynamics constituted about 71 percent of the program's FY 1993 budget ($937 million). Ecological Systems and Dynamics received 17 percent of the budget ($224 million). The remaining 12 percent of the budget ($165 million) was divided among the remaining four research elements: Earth System History, Human Interactions, Solid Earth Processes, and Solar Influences (8).

Projects are categorize as *focused--directly* relating to global change--or *contributing*—justified on a basis other than global change but having the potential to contribute to the global change knowledge base (see fig. 3-7).[11] Even when both focused and contributing research are considered, 70 percent of all funds is targeted for

10 Most of the funds for modeling and prediction go toward nonmodeling process research. The major modeling groups have received only a small portion of these funds,

11 Unless specifically noted, budget figures refer to the focused budget.

Figure 3-5-USGCRP Focused Budget by Activity Stream



NOTE: Total budget does not include one-time appropriation of $5 million for the State Department in FY 1993 because the distribution of funding among proposed projects is still being determined. The budget for the FY 1994 Assessment activity stream is embedded in the other three activity streams. FY 1994 values are the requested, not the appropriated, amounts.

SOURCE: Committee on Earth and Environmental Sciences (CEES), *Our Changing Planet: The FY 1994 U.S. Global Change Research Program* (Washington, DC: CEES, 1993).

projects in the first two priority research areas. There are no standardized criteria for classifying contributing research, and each agency uses its own system. Consequently, it is difficult to know precisely the extent of contributing research or to get a comprehensive picture of relevant research. Both focused and contributing programs are considered in a procedure called the "budget crosscut.' USGCRP is one of only a few Federal programs that uses a budget crosscut as a coordinating mechanism. This approach has been reasonably successful in facilitating cooperation and securing new funding for global change research. The USGCRP budget-crosscut process works as follows.

Each program within an agency submits new projects to the appropriate subworking group of CEES. This subworking group determines whether to recommend to the agency that the project be included in USGCRP (projects can be added later in the budget process, but this is the most likely step at which new projects are added).

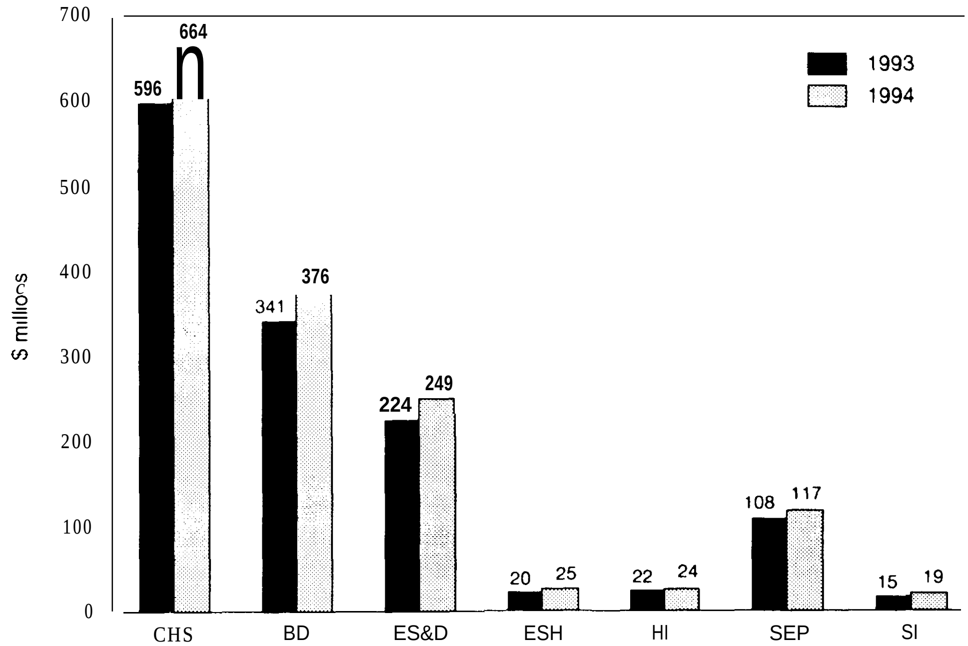
Each agency that participates in USGCRP then develops its own GCRP budget, with some coordination between agencies for joint projects. These budgets are then submitted to CEES, which may continue to negotiate with the agencies. CEES submits one budget proposal incorporating programs from all participating agencies to the Office of Management and Budget (OMB). When the proposal reaches OMB, it is initially reviewed at one meeting by all of the budget examiners for the various agencies involved in USGCRP. Although one examiner takes the lead for USGCRP, the participation of the other examiners is critical because each must understand the purpose of the USGCRP projects that fall within his or her agency's budget. The USGCRP budget is returned to each agency when that agency's whole budget is returned. At that point, deliberations between OMB and the agencies proceed as normal. As agencies work to meet OMB-established budget targets, they look at modifying all projects—they can accept or reject OMB'S recommendations and reprogram their global change budgets.[12] The final USGCRP budget is presented to Congress along with the annual Presidential Budget Request.[13] When the program first started, approximately 70 percent of the proposed budget consisted of research funds from already existing projects.

The USGCRP budget falls within the jurisdiction of several congressional authorization and appropriations committees and subcommittees (see table 3-2). With all of these committees reviewing components of the USGCRP budget, it

12 During the first few years of the program, USGCRP required agencies to "fence off," or commit, *their global change* research budget requests to the program. They could not reprogram this money later if OMB cut overall agency funding further down the line.

13 The first two budget requests were long, detailed documents accompanied by executive summaries, but since FY 1992, only the summaries have been published. USGCRP staff determined that the information in the detailed budgets changes slowly and, therefore, needs to be published only every 5 years.

Figure 3-6--USGCRP Budget by Science Element



NOTE: CHS-Climate and Hydrologic Systems; BD=Biogeochemical Dynamics; ES&D= Ecologcal Systems and Dynamics; ESH=Earth System History; H-Human Interactions; SEP=Solid Earth Processes; SI=Solar Influences. FY 1994 values are the requested, not the appropriated, amounts.

SOURCE: committee on Earth and Environmental Sciences (CEES), *Our Changing Planet: The FY 1994 U.S. Global Change Research Program* (Washington, DC: CEES, 1993).

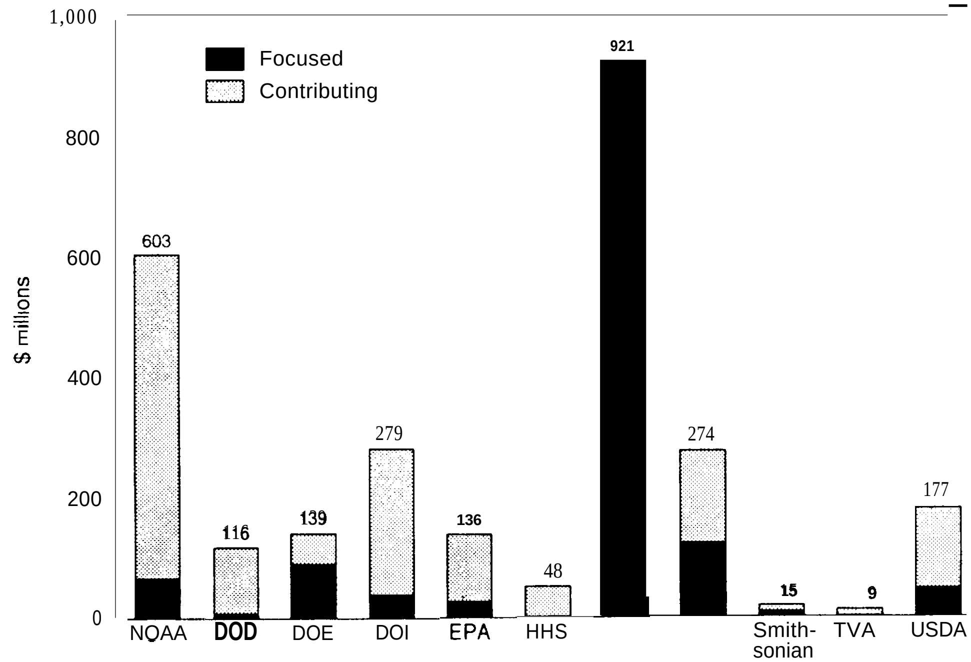
is much more difficult for Congress to consider the USGCRP budget as a whole than it is for the executive branch to do so. Several members of Congress have complained about the fragmentation of congressional attention to the USGCRP budget, but no alternatives have been proposed. It might be useful for Congress to consider using an ad hoc appropriations subcommittee consisting of members from the committees with primary jurisdiction over elements of USGCRP to review the program's budget as a comprehensive unit. If two or three agencies are cooperating on a single project, but one agency does not receive funding for it, the entire project could beat risk.[14] Large, interagency programs such as USGCRP will require innovative methods of funding if they are to succeed.

■ Satellite vs. Nonsatellite Measurements

NASA'S Mission to Planet Earth (MTPE) program accounts for over 60 percent of USGCRP focused funding (crossing several of the priority research areas). The core of the MTPE program is the development and maintenance of the Earth Observing System (EOS), an ambitious satellite program originally designed to provide

[14] For example, at OTA's workshop "EOS and USGCRP: Are We Asking and Answering the Right Questions?" (Feb. 25-26, 1993), participants cited programs such as the World Ocean Circulation Experiment (WOCE), Tropical Oceans Global Atmosphere (TOGA), and the Joint Global Ocean Flux Study (JGOFS)(50). All three arc interagency research programs where the success of the entire program depends on contributions from NASA, the National oceanic and Atmospheric Administration and the National Science Foundation. However, in a recent budget cycle, NASA received more than it asked for these programs while NOAA and NSF received no money. Rather than let the programs die, NASA filled the financial gap left by inadequate funding for NOAA and NSF.

Figure 3-7--FY 1993 USGCRP Budget of Focused and Contributing Programs by Agency

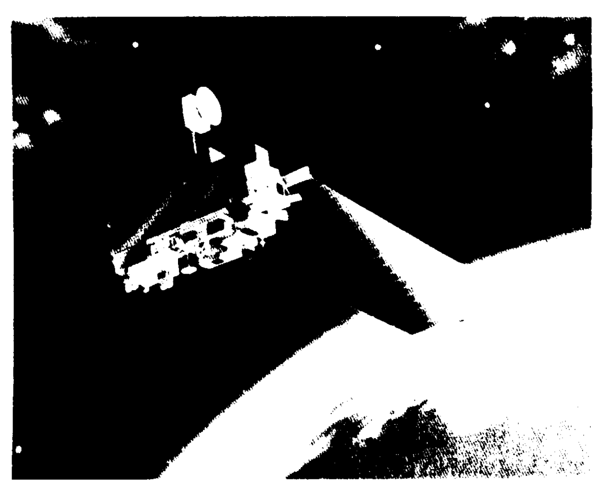


NOTE: For definitlon of terms, see table 3-1.

SOURCES: Committee on Earth and Environmental Sciences (CEES), *Our Changing Planet: The FY 1993 U.S. Global Change Research Program* (Washington, DC: CEES, 1992); Office of Technology Assessement, 1993.

data over a 15-year period related to the study of precipitation; ocean circulation; sources and sinks of greenhouse gases; changes in land use, land cover, hydrology, and ecology; changes in glaciers and ice sheets; ozone; and volcanic activity. Because of EOS'S central role in NASA's USGCRP effort and the great expense of putting satellites in space, the USGCRP budget as a whole is heavily weighted toward satellite-based measurements.[15]

EOS has suffered extensive restructuring over the past few years, which may jeopardize the quality of information gained from remaining EOS instruments. Some instruments that were supposed to have improved the understanding and observation of possible climate change impacts



Artist's conception of NASA's Earth Observing System (EOS). EOS (AM-1 Platform) is scheduled to be launched in 1998.

[15] Although about 50 percent of NASA's USGCRP budget is classified as nonsatellite programs, most of these support data maintenance and operation of the satellite programs.

Table 3-2-Congressional Authorization Committees and Appropriations Subcommittees with Significant Legislative Authority over Agencies with a USGCRP Component

House and Senate Authorization Committees	Jurisdiction[a]
House	
Agriculture	USDA
Armed Services	DOD, DOE
Energy and Commerce	DOE, HHS
Natural Resources	DOE, USDA/FS, SI
Sciences, Space, and Technology	NASA, NSF, DOE, EPA, NOAA, S1
Public Works and Transportation	NOAA, SI
Merchant Marine and Fisheries	USDA, NOAA, SI
Senate	
Agriculture, Nutrition, and Forest~	USDA
Armed Services	DOD, DOE
Commerce, Science, and Transpodation	NSF, NASA, NOAA
Energy and Natural Resources	DOE, DOI
Labor and Human Resources	DOE, DOI, HHS
Environmental and Public Works	EPA, SI
Rules and Administration	SI
House and Senate Appropriations Subcommittees	
Labor, Health and Human Services, and Education	HHS
Housing and Urban Development and Independent Agencies	NASA, NSF, EPA
Energy and Water Development	DOE
Interior and Related Agencies	DOE, USDA, DOI, SI
Agriculture and Rural Development[b]	USDA
Commerce, Justice, State, and Judiciary	NOAA
Defense	DOD

[a] For definition of terms, see table 3-1.

[b] The corresponding subcommittees of the Senate and House Committees on Appropriations have the same name with one exception: the Senate Subcommittee on Agriculture, Rural Development, and Related Agencies and the House Subcommittee on Rural Development, Agriculture, and Related Agencies.

SOURCES: U.S. Congress, Office of Technology Assessment (OTA), Federally *Funded Research: Decisions for a Decade, OTA-SET-490* (Washington, DC: Government Printing Office, May 1991); Office of Technology Assessment, 1993.

have been dropped or postponed. For example, the High Resolution Imaging Spectrometer (HIRIS), an instrument potentially capable of resolving some of the more subtle aspects of ecological change that cannot be detected by satellites today, was originally scheduled to be part of EOS, but was dropped during program restructuring (54). EOS began as a $30 billion program, but was scaled back to an $8 billion program (see box 3-A).[16]

Most participants at OTA'S workshop "EOS and GCRP: Are We Asking and Answering the Right Questions?" agreed that had EOS been designed initially to be an $8 billion program, it likely would be different from the program we have today. All acknowledged that much good data will be collected and good science will be done through EOS, but that it will provide neither the continuous, multidecade data set necessary for ecosystem studies nor a true global monitoring

[16] For more discussion of EOS, see references 49 and 50.

Box 3-A–Remote Sensing as a Tool for Coping with Climate Change

Remote sensing is the observation of the Earth from a distance. The ability to view and monitor large areas of the Earth has become valuable in understanding regional and global-scale phenomena such as weather systems, deforestation rates, and, most recentty, climate change. Remote sensing can help reduce the uncertainties associated with climate change in two ways: 1) by improving climate predictions through better understanding of atmospheric and climate processes and 2) by improving scientists' ability to detect and predict the effects of climate change on the biosphere. Both uses of remote sensing would be important for coping with climate change. However, most biosphere-related climate research to date has focused on the former, whereas relatively little has focused on the latter. This box examines the uses and limitations of remote-sensing technologies for observing, detecting, and understanding changes in the biosphere resulting from climate change, land-use change, or other factors.

Development of remote-sensing technology

Airborne sensors-The oldest form of remote sensing-invented about 100 years ago—consists of photographs taken from balloons. The development of the airplane made aerial photography the primary way to monitor and study the Earth's surface from a distance. Scientists also discovered that images created from other parts of the electromagnetic spectrum (i.e., the infrared region) could provide additional information about surface characteristics, such as mineral composition, soil moisture, and crop condition.

The U.S. Forest Service has been using aerial photography since the 1930s to measure the area of forests, monitor forest health, and plan timber harvests. Aerial photography is also an important tool in the U.S. Fish and Wildlife Service's National Wetland Inventory Program. The technique is best suited for observing relatively small areas and for studies requiring a high level of spatial detail. Riparian wetlands and wetlands less than 5 acres (2 hectares)[1] in area, for example, cannot be accurately characterized by satellite-based observations (18). Therefore, aerial photography is an essential tool for comprehensive wetland monitoring.

However, using aerial photography to get consistent coverage overlarge areas for regional analysis is very difficult and costly. The aerial photography technology used frequently by the National Aeronautics and Space Administration (NASA) for ecological studies can cost about $10,000 per flight. Difficulties also lie in determining exactly where the plane is in space so that the area being photographed can be precisely identified. Also, taking photographs at different times from exactly the same vantage point is difficult. Although aerial photography may be preferable for ecological applications requiring high levels of detail (e.g., wetland inventory and forest monitoring), it is not practical for routine, regular measurements or for studies of targe-scale ecological phenomena.

Remote sensing from satellites-By the late 1960s, advances in technology made transmitting electronic images to Earth from satellite-based instruments practical. Polar-orbiting satellites (orbits pass over both the North and South Poles) allow imaging of the entire globe. These Earth observation satellites are equipped with various sensors that detect natural radiance (electromagnetic waves emitted by surface features) and reflectance (those reflected from Earth's surface).[2] The intensity and wavelength of the signal detected become a type of signature for certain surface features. By combining these signals, various vegetation types and other characteristics can be identified.

1 To convert acres to hectares, multiply by 0.405.

2 Sunlights absorbed by Earth's atmosphere, scattered and reflected Off Earth's Surface, or absorbed by its surface. Surface features that absorb some waves can re-emit electromagnetic signals-often at longer wavelengths. In generat, reflected (or scattered) signals give information about the structure of the surface features, and radiated signals give information about its chemical composition.

(Continued on next page)

Box 3-A–Remote Sensing as a Tool for Coping with Climate Change—Continued)

Satellites include several instruments that monitor Earth with “passive sensors” designed to detect a narrow range, or window, of various parts of the electromagnetic spectrum. These windows are called *spectral bands.* By detecting different parts of the spectrum, a variety of signatures is obtained. Being able to detect narrower bands improves the ability to categorize detected signatures by wavelength. More narrow bands over a wider range of the spectrum enables detection of more signatures, which improves the ability to discern closely spaced objects and identify surface features. Identification of a wetland, for example, generally requires analysis of three or more infrared spectral bands (18): one discriminates amounts of vegetation, water, and soil moisture; another helps determine water quality; and another helps to classify different vegetation types. However, detailed geographic and spectral resolution is more expensive, requires higherdata-collection rates, and limits spatial coverage (49). Passive optical sensors detect only surface features. They cannot be used for Earth observation through clouds, accurate measurement of soil moisture through dense vegetation cover, or detection of submerged vegetation. Radar instruments have “active” sensors that provide their own illumination via microwave pulses and then measure the reflected energy. Unlike optical sensors, radar data can be acquired through clouds and at night. Radar signals are especially sensitive to water and may improve the way soil and vegetation moisture are measured (53, 54). In addition, radar can probe to greater depths and may provide better information about surface roughness, canopy height, and, perhaps, vegetation beneath a dense canopy than can optical sensors (53,54).

Several countries besides the United States, including France, Japan, India and Russia have launched satellites for environmental studies and Earth observation. Discussed below are satellites whose data are most widely used by U.S. scientists for detecting change in the biosphere and for large-scale ecosystem studies.

Advanced Very High Resolution Radiometer (AVHRR)-This scanning radiometer, aboard NOM’s Polar Orbiting Environmental Satellite (POES), uses five detectors to create surface images in five spectral bands (49). AVHRR data allow multispectral analysis of vegetation, clouds, lakes, coasts, snow, and ice and have been used to monitor crop conditions, classify global vegetation, and demonstrate the scale of deforestation in the tropics (44). AVHRR provides daily coverage of the Earth, allowing frequent monitoring of a large region and the creation of virtually aloud-free images at a fraction of the cost and computing time required for aerial photography or other satellite technologies (43).[3] Although PMHRR data have much lower spatial resolution than do data from aerial photography—about 0.7 miles (1.1 kilometers)[4] per pixel, or data point—0.6-mile to 16-mile resolutions are adequate for “assessing many global or regional trends in land cover, vegetation damage, deforestation, and other environmental conditions” (44).

Landsat-in 1972, NASA launched the first of a series of Landsat satellites for civilian Earth observation and monitoring. Now, a 20-year continuous data set has been acquired for some selected areas (primarily in the United States and the former Soviet Union), making Landsat data the primary source of data for detecting long-term ecological trends. This long-term record is just now beginning to provide valuable information about trends and changes in wetland area, vegetation types, forest growth, deforestation rates, and urban expansion.

Consistency in measurement is very important for maintaining accurate and useful long-term records. Landsat missions have been designed so that data from different missions can be compared while allowing moderate advances in technology. Sustaining Landsat missions and maintaining a continuous data set over 20 years has not been easy. Over this time, operation of Landsat has changed from public to private and back to public

3 The EROS Data Center makes global data sets that are almost aloud-free by imaging over approximately 10 days.

4 To convert miles to kilometers, multiply by 1.609.

hands.[5] These changes have threatened to limit the availability of data to users, have increased the costs of data to users, and have limited the number of scenes imaged. Landsats 4 and 5 have already surpassed their expected life spans by several years. The recently launched Landsat 6 (October 1993) never reached orbit, and the long-term Landsat record is now threatened.

The main advantage of Landsat and similar satellites is that they can distinguish surface features with higher spatial and spectral resolution and broader spectral coverage than do AVHRR data.[6] Landsat data have been used to identify and monitor crops, classify forest stands with finer classification scales, and assess damages from natural disasters. However, Landsat provides less frequent coverage of an area (every 16 days) and requires more computing time and power than do AVHRR data sets. For these reasons, AVHRR is more widely used than Landsat for global data analyses. Landsat data sets are also significantly more expensive than are AVHRR data sets. According to one scientist, "The 10-times-greater expense and 1,000-times-greater data volume [of Thematic Mapper of Landsat (TM) data as opposed to AVHRR data preclude] use of multiple annual [Landsat] data sets for global studies" (43). (The cost of each 120- by 110-mile scene is about $5,000 (18)).

New technologies[7]—Instruments considered for Landsat 7 will improve surface resolution and allow the creation of topographic images (by having the ability to point to the side), thereby increasing Landsat's revisit frequences from once every 16 days to once every 3 days (49). Until recently, a High Resolution Imaging Spectrometer (HIRIS) was under consideration for development as part of NASA's Earth Observing System (EOS) program. In principle, HIRIS data could be used to detect specific species of trees or other ground cover, track pollutants in water, and identify natural vegetation that is under stress. A Synthetic Aperture Radar (SAR) proposed for EOS—but recently canceled—would have been capable of multiangle, multifrequency, and multipolarizartion measurements (49). SAR could have measured soil moisture under vegetated land, determined the vertical structure of vegetation canopies, and measured canopy moisture (53). However, both HIRIS and SAR were dropped from consideration because of high costs and launch requirements (54).

Uses of remote sensing under climate change[8]

Many questions about climate change impacts and how to respond to them remain unanswered. For example, which plant and animal communities are likely to change first? How will they change? How fast will changes occur? Which species are already declining? Why? Where? Which are flourishing? Satellite data are already being used to answer many questions related to large-scale ecological change, but limitations in both satellite technology and in ecological understanding prevent some of the most compelling questions about global ecological change from being addressed with satellite data. The table in this box (next page) lists some potential uses of remote-sensing data.

Remote sensing for scientific study—Although an Earth observation satellite has never been launched specifically for ecological studies (41), current operating satellites can help reveal some important aspects of

[5] Landsat 4 and 5 are operated and maintained by the Earth Observation Satellite Company (EOSAT), a private company. Landsat 6 will be launched by the U.S. Government but operated by EOSAT (16). The Land Remote Sensing Policy Act of 1992 (P.L. 102-555) transfers all control of future Landsat missions (starting with Landsat 7) to the Department of Defense and NASA (49).

[6] Landsat 4 and 5 carry the Thematic Mapper (TM) sensor, providing 100-foot (30-m) ground resolution in six spectral bands (one thermal infared band has a 390-foot (120-m) resolution). Landsat 6 is scheduled for launch on September 5, 1993, and will carry an Enhanced Thematic Mapper imaging instrument (ETM). ETM will improve the TM by adding a 5-foot resolution panchromatic sensor, making it possible to collect data streams with sharper resolutions and increase vegetation discrimination.

[7] See *The Future of Remote Sensing from Space: Civilian Satellite Systems and Applications* (49) for a more complete discussion of the future of remote-sensing technologies.

[8] Much of this section was developed from a workshop, "Ecology and Remote Sensing," held September 18, 1992, at the University of Maryland at College Park.

(Continued on next page)

Box 3-A—Remote Sensing as a Tool for Coping with Climate Change—(Continued)

Potential uses of current remote-sensing data for biosphere study

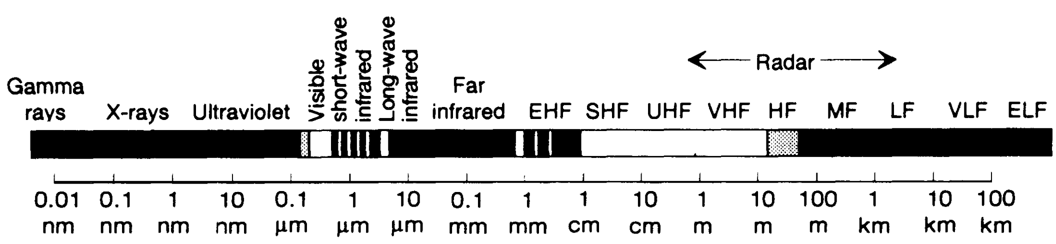
- Classify land-surface cover
- Detect vegetation-climate relationships
- Detect frequency and extent of fire
- Detect inundation extent
- Detect surface soil moisture in areas of low vegetation cover
- Detect land and ocean surface temperature
- Calculate ocean color indices
- Calculate vegetation indices
- Estimate global net primary production
- Estimate ranges of evapotranspiration
- Measure horizontal canopy structural characteristics
- Measure canopy biochemical constituents
- Measure vegetation water content

Potential uses of future remote-sensing data[a]

- Classify vegetation cover by community types or species assemblages
- Detect and monitor margins of ecosystems
- Detect successional stages in forests
- Characterize vegetation stress (in natural communities as well as in crops)
- Estimate contaminant concentrations in water and snow
- Estimate biochemical composition of vegetation canopies in more detail
- Estimate canopy structural characteristics with independent methods
- Estimate biomass
- Estimate extent of deforestation
- Measure soil moisture in vegetated areas
- Measure vertical canopy structural characteristics
- Measure canopy biochemical constituents in more detail
- Measure canopy moisture content
- Measure canopy height

[a] Some uses may require further research in order to be proven.

SOURCES: U.S. Congress, Office of Technology Assessment (OTA), Ecology and Remote Sensing Workshop, Center for Global Change, University of Maryland at College Park, Sept. 18, 1992; U.S. Congress, Office of Technology Assessment (OTA) workshop, "EOS and USGCRP: Are We Asking and Answering the Right Questions?" Washington, DC, Feb. 25-26, 1993; S.L. Ustin et al., "Opportunities for Using the EOS Imaging Spectrometers and Synthetic Aperture Radar in Ecological Models," *Ecology*, vol. 72, No. 6, 1991, pp. 1934-45; D.E. Wickland, "Mission to Planet Earth: The Ecological Perspective," *Ecology*, vol. 72, No. 6, 1991, pp. 1923-33.



Most of the energy that is reflected, absorbed, or scattered by the Earth's atmosphere is visible or shortwave infrared energy (from 0.4 to 4 microns). In the thermal infrared, most attenuation is by absorption. Short-wavelength radiation is reflected by clouds, water vapor, aerosols, and air; scattered by air molecules smaller than radiation wavelengths; and absorbed by ozone in shorter wavelengths (<0.3 micron) and by water vapor at the longer visible wavelengths (>1.0 micron).

SOURCE: A. M. Carleton, *Satellite Remote Sensing in Climatology* (Boca Raton, FL: CRC Press, 1991).

changing ecosystems and the consequences of various impacts on the biosphere. Most importantly, satellite data have allowed the biosphere to be studied from a new perspective and at much larger scales than ever before, opening up a whole new area of ecological study. The most direct application of satellite data is the detection and study of land-use change. Because satellite data can be used to discern broad classes of vegetation (e.g., grasslands, crops, evergreen forests, and deciduouos forests), it has been an important toll in studying the extent of deforestation in the tropics and the extent of desertification in Africa.

Leaf area, which can be calculated from remote-sensing data, has been used for identifying more specific types of vegetation cover of large vegetated areas. A leaf Area Index (LAl) is being used to identify the extent of specific crops (such as wheat) and their stress levels throughout the growing season. It is also being used to monitor the condition of rangelands, pastures, and other mostly homogeneous land cover. This technique is less useful for natural vegetation where suboptimal growing conditions and a mix of species make the links among LAI, vegetation type, and health weak.

Remote sensing has also been used to monitor soil-moisture conditions in areas where-and during seasons when—vegetation cover is sparse, but it cannot measure ground soil moisture in heavily vegetated areas. Thus, satellite images miss most forested wetlands. Coastal erosion and some processes of large, shallow, open wetlands (such as those in the Mississippi River Delta) can easily be studied and monitored over time with remote-sensing data. For adequate delineation of wetlands, many wetland scientists believe that color infrared data at a I6-foot (5-meter)[9] resolution viewed in stereo is required (18). Landsat 7 may be able to get this kind of resolution for wetland delineation, but wetland scientists studying the larger-scale processes of coastal wetlands would rather have a coastal contour map at l-foot contour intervals than improved satellite remote-sensing technology (50).

Remote-sensing data have been used for mapping forest evapotranspiration and photosynthesis—key processes that control the exchange of energy and mass in terrestrial vegetation. Climate change will likely perturb patterns of evapotranspiration and photosynthesis. Regional maps of these processes will help researchers detect and understand such change.

Remote sensing for land-management and planning—Remote-sensing data are being used in conjunction with data from other sources as a tool for land management and planning. For example, the Fish and Wildlife Service launched the Gap Analysis Project (GAP) in 1991 to identify areas of potentially high biodiversity and their protection status to guide future land acquisitions and habitat-protection efforts. Remote sensing (mostly Landsat data) is the primary tool used to identify vegetation types (see vol. 2, box 5-J).

In addition, Geographic Information Systems (GISS) have been developed and used throughout Government agencies for regional analyses and planning. Vegetation and land-cover information from remotely sensed data is combined with digitized geologic, geographic, hydrologic, and topographic data in one computer system, so that one overlay containing all this information can be studied and used to test potential land-use decisions (such as altering the hydrology). Such analyses can lead to a better understanding of the Earth's surface and subsurface processes and more sound regional land-use planning near environmentally sensitive areas (see vol. 2, box5-J).

Ducks Unlimited uses remotely sensed data from satellites in combination with aerial photography from the Fish and Wildlife Service's National Wetlands Inventory project for wetland monitoring. For their purposes, combining National Wetlands Inventory digital data with satellite data for evaluating wetland functions is more valuable than using either product alone (18).

Current satellite data are useful for studying ecological processes on a very large scale, but are relatively inadequate for detecting more subtle ecological changes, such as those at ecotones, at the edges of ecosystems, or within an individual plant community. "Satellite data cannot match the extent, classification detail, or reliability" of data from aerial photography and other manual techniques used in the National Wetlands Inventory Project (18).

[9] To convert feet to meters, multiply by 0.305.

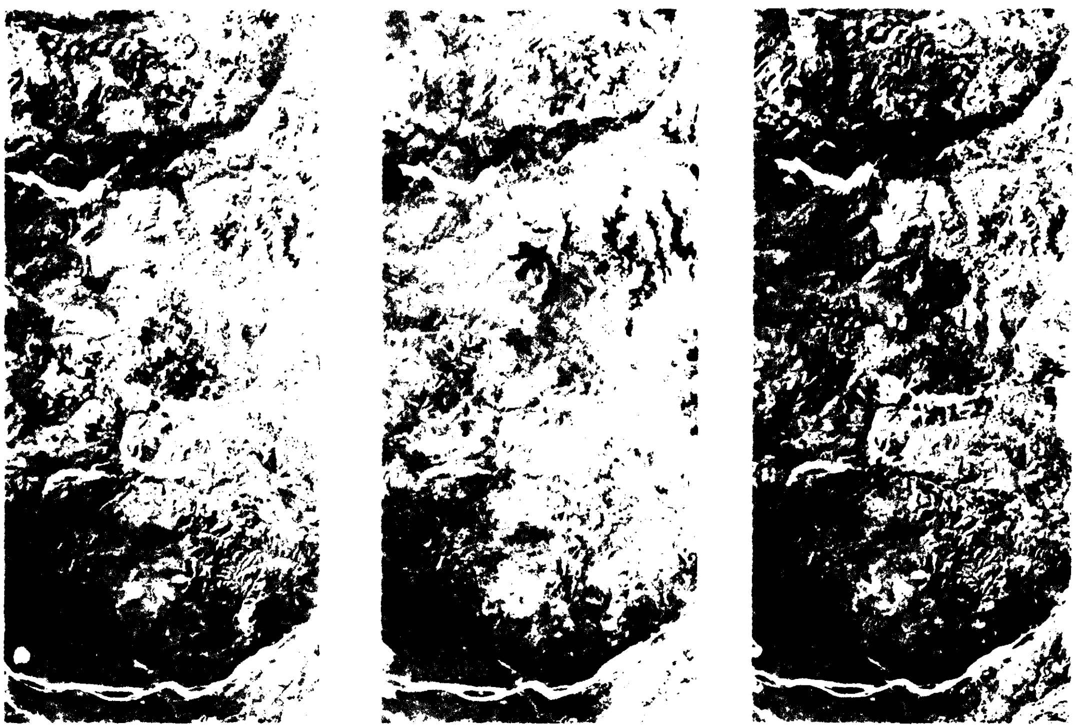
(Continued on next page)

Box 3-A-Remote Sensing as a Tool for Coping with Climate Change—Continued)

Limitations to broader applications of remote sensing

The principal drawbacks of satellite data for detecting impacts of climate change are their limited spatial and spectral resolution. Remote sensing can be used to determine broad classes of vegetation, but it cannot identify species or communities. With satellite-based information, it is nearly impossible to study the more subtle aspects of regional ecological change. These include vegetation health in natural areas and mixed forests, ecological change at ecosystem boundaries, migration of a single species or even a species community, drought conditions and soil-moisture trends in heavily vegetated areas, and exact rates of wetland loss. Furthermore, few ecologists are skilled at studying ecosystems at large, cnarse-resolution scales.

Technology is available to expand applications of sateillte remote sensing for studying impacts of climate change, but high costs, launching requirements, and scientific priorities have delayed its development. Even current satellite data have not been used to their full potential for studying potential impacts of climate change. For example, large-scale studies of the biosphere are limited by the availability of data sets. The only global vegetation data set available is the Global Vegetation index (GVI), generated from AVHRR data. Even a



Landsat MSS Image September 15, 1973

Landsat MSS Image May 22, 1983

Landsat MSS Image August 31, 1988

LANDSAT/U.S. GEOLOGICAL SURVEY

Landsat data have been used to identify and monitor crops, classify forest stands, and assess damages from natural disasters. These Landsat images of Mount St. Helens show the area in 1973 before the volcano erupted and in 1983 and 1988, after the volcano erupted.

consistent, calibrated, single-source map of U.S. land cover and land use does not exist. More detailed coverage of large areas on the global or continental scale is limited by high costs and data volume. In fact, many university researchers have started to study AVHRR data despite its limited resolution and spectral information because of the high costs of Landsat data.

Another factor that limits wider use of remotely sensed data stems from differences among scientific disciplines. Many ecologists, for example, are not trained to use satellite data (41), and those who use remote-sensing technologies are typically not mainstream ecologists. There has never been a remote-sensing instrument designed specifically for ecological studies (41). Furthermore, few remote-sensing scientists have backgrounds in ecology or biology (41). Ecologists must essentially take what they can get from remote-sensing data that may not be optimal for their field. Opportunities for interdisciplinary studies at universities and the relatively recent surge of interest in *ecosystem* research (spurred by climate change, deforestation, and global pollution) may help to bridge the gap.

SOURCE: Office of Technology Assessment 1993.

network. Both these shortcomings are important to consider in future discussions about the science base of USGCRP. Many correlative measurements made with airborne platforms or ground-based instruments (that would verify and calibrate the satellite measurements and provide continuous coverage when satellites are not operating) were originally planned to be part of USGCRP but were not funded. Costs for such efforts could be a small percentage of the USGCRP budget—in the tens of millions of dollars each year.[17]

The Landsat satellite monitoring program is of significant ecological interest because it is the primary source of data for detecting long-term ecological trends (18).[18] Landsat satellites contain instruments that analyze multispectral data to obtain images of the Earth (see box 3-A). New technologies have allowed resolution to improve from about 100 feet (30 meters)[19] to a few feet. Landsat data allow changes to be detected in vegetation type and cover, hydrologic patterns, extent of wetlands, land use, and soil moisture. It is the only satellite monitoring program that has a 20-year data set, despite several changes in ownership and new technology over the years that nearly resulted in its termination. The data are just now becoming relevant for ecological studies of changes in vegetation cover due to natural processes. Multidecade data sets are vital to global change research; however, consistency is extremely difficult because the average life of a satellite is only 5 years. A central element of an extended set of missions must be ensuring the compatibility of future satellite data with current data while accommodating new technologies. In addition, subsequent satellites must survive fiscal fluctuations.

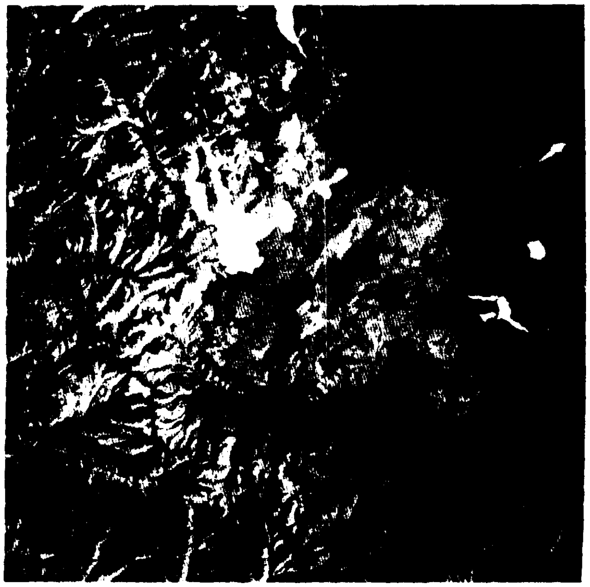
■ Balance Among NASA and Other USGCRP Agencies

The question of balance between satellite and nonsatellite measurements is directly connected to the question of balance among participating USGCRP agencies. Currently, NASA, the National Oceanic and Atmospheric Administration (NOAA), and the Department of Energy (DOE)

17 OTA's workshop "EOS and USGCRP: Are We Asking and Answering the Right Questions?" Washington, DC, Feb. 25-26, 1993.

18 Landsat receives approximately 25 percent of its budget from NASA and 75 percent from DOD, It is apart of NASA's Mission to Planet Earth, but it is separate from EOS.

19 To convert feet to meters, multiply by 0.305.



This Landsat photo of Yellowstone National Park demonstrates the different hand-use patterns in the vicinity of the park. A clear line, formed by different land-use patterns, delineate the park boundary. The area spans three States and is managed by Federal, State, private, and tribal landowners. The Federal portion of the area comprises two National Parks, nine National Forests, and land owned by the Fish and Wildlife Service and the Bureau of Land Management. (See vol. 2, ch. 5, box 5-F.)

control 80 percent of the focused research budget for USGCRP. Even when contributing programs are considered (e.g., those that are ongoing for other reasons), NASA, DOE, and NOAA control 60 percent of the USGCRP budget (see figs. 3-4 to 3-7). The lack of participation by agencies other than NASA has led to gaps in the overall program. For example, DOI, which manages approximate ly 500 million acres (200 million hectares)[20] of public land that could be affectedly climate change, requested a decrease in USGCRP funding for both FY 1993 and FY 1994. This can be attributed partly to management agencies focusing their resources on what they perceive as more immediate management concerns.

Another dimension of the imbalance in agency participation is the historical attraction that Congress and the executive branch have had for space-based research. Federal agencies may correctly perceive that it is easier to get financial support for large, space-based projects than for lower-profile research such as monitoring (36, 55).

NASA'S contribution dwarfs contributions from other agencies, but it is unclear how to bring more balance to the program to help fill the gaps and make the necessary links to other global change issues. Because USGCRP does not have a program budget, it would be difficult to redistribute funds across agencies; however, there might be Opportunities to modify projects within agencies to help meet the needs of global change research.

ADAPTATION RESEARCH IN THE FEDERAL GOVERNMENT

The Mitigation and Adaptation Research Strategies program was created about the same time as USGCRP and operated as an independent working group under CEES. MARS was conceived to develop "a coordinated Federal research strategy for mitigation of, and adaptation to, global change and with assessment of economic, social and environmental effects of the proposed responses. The program addressed four functions: mitigation, adaptation, economics, and social dynamics (5). MARS objectives under its adaptation program were to:

1. determine the sensitivity and adaptive capacity of human and other natural systems to global change, and the social, cultural, economic, and other constraints or impediments to implementation of adaptive measures and methods to reduce those constraints;
2. determine the mechanisms and timing required for current evaluation procedures and practices to be modified to meet soci-

~ To convert acres to hectares, multiply by 0.405.

ety's needs to accommodate global change, given the uncertainties about the timing and magnitude of global change and its effects; and

3. identify, develop, demonstrate, and evaluate technologies and strategies to adapt to global change.

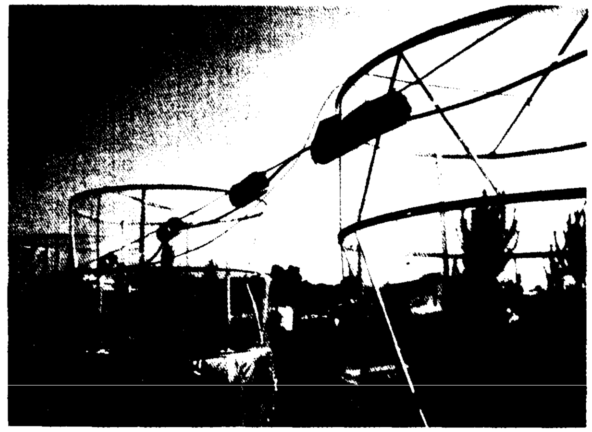
These objectives were to be directed toward water resources; natural systems; food, forestry, and fiber; and human systems. In a sense, MARS was charged with conducting all the research components missing from USGCRP.

However, MARS did not receive the administrative backing that USGCRP did and never developed an interagency research program on mitigation and adaptation research. By 1992, MARS, as a formal entity, ceased to exist. Under the CEES Subcommittee on Global Change, an informal, and later formal, Subcommittee on the Environment and Technology formed in 1992, which continues to address mitigation and adaptation issues, but in a much broader context. Although this subcommittee has no budgetary power, it is holding the door open for agencies with more interest in applied climate change research than in basic research, such as the Environmental Protection Agency, the Department of Housing and Urban Development (HUD), the Tennessee Valley Authority, the U.S. Department of Agriculture (USDA), and the Department of the Interior, to redirect their funds to this end.

Although MARS provided a forum for agencies to discuss global change programs of mutual interest, it was unable to exercise any influence over project selection and funding. Consequently, MARS served primarily to identify existing agency programs and projects that addressed mitigation, adaptation, social dynamics, and economic issues either as a main focus or as a contributing element.

Research "Focused" on Adaptation

MARS classified only a handful of projects as focused on adaptation research, and funding for


U.S. FOREST SERVICE

Three-level, open-top chambers, such as these at Finley Farm, North Carolina, can be used to study the effects of increased carbon dioxide, ozone, and drought stress on trees and plants.

these projects totaled $8.18 million in FY 1992 (5) (see table 3-3A). These projects are not included in USGCRP per se because they do not conform to the USGCRP mission of "observe, understand, and predict."

Of the $8.18 million considered focused on adaptation research, NOAA spent $4.1 million, or close to 50 percent, the National Science Foundation (NSF) and EPA each spent $1.2 million, or 15 percent, each, and USDA spent $0.35 million, or 4 percent, of the total spent on adaptation research. DOI, the department that houses land-management agencies responsible for 500 million acres of public land, was conspicuously absent from the MARS list of agencies undertaking focused adaptation research.

Examples of focused adaptation research include: a $200,000 NSF program on the effects of climate change on coastal zones; a $1.1 million USDA program that seeks to simulate the effects of changing climate and management practices on organic matter, crop yields, and rangeland productivity; a $20,000 TVA program on regional climate scenarios; a $30,000 TVA program addressing the sensitivity of the TVA reservoir and power supply systems to extreme meteorology; a $250,000 Department of Defense (DOD) program that assesses the impacts of potential climate

Table 3-3A-FY 1991 and 1992 Focused Research by Agency and Function ($ millions)

	Totals		Mitigation		Adaptation		Economics	
Agency[a]	1991	1992	1991	1992	1991	1992	1991	1992
DOC	**3.3**	**5.1**	**0.1**	**1.0**	**3.2**	**4.1**		
DOD		1.1				1.1		
DOE	1,7	2.2	1.7	2.2				
DOS	<0,1	0.1			<0. 1	0.1		
DOT		0.2				0.2		
NSF	1.2	1.2			1.2	1.2		
USDA		3.5		2.1		0.4		1.0
EPA	3.3	3.3	2.4	2.1	1.0	1.2		
Totals	9.5	16.5	4.1	7.3	5.4	8.2		1.0

[a] DOS= Department of State; DOT= Department of Transportation. For definition of other terms, see table 3-1.

SOURCE: Committee on Earth and Environmental Sciences (CEES), Mitigation and Adaptation Research Strategies Working Group, MARS Working *Paper /: Description of Proposed Coordinated Program* (Washington, DC: CEES, 1992).

Table 3-3B--FY 1991 and 1992 Focused Adaptation Research by Agency and Element ($ millions)

	Totals		Natural Systems		Human Systems		Food, Forestry, and Fiber		Water Systems	
Agency[a]	1991	1992	1991	1992	1991	1992	1991	1992	1991	1992
DOC	3.2	4.1	0.7	1.1	0.4	1.0			2.2	2.0
DOD		1.1								1.1
DOS	< 0.1	0.1	< 0.1	0.1						
DOT		0.2				0.2				
NSF	1.2	1.2			1.2	1.2				
USDA		0.4		0.1		0.1		0.1		0.1
EPA	0.9	1.2	0.3	0.4	0.2	0.3	0.2	0.3	0.2	0.3
Totals	5.4	8.2	1.0	1.6	1.8	2.8	0.2	0.3	2.4	3.4

[a] DOS= Department of State; DOT= Department of Transportation. For definition of other terms, see table 3-1.

SOURCE: Committee on Earth and Environmental Sciences (CEES), Mitigation and Adaptation Research Strategies Working Group, *MARS Working Paper/: Description of Proposed Coordinated Program* (Washington, DC: CEES, 1992).

change on water resource management; and a $50,000 DOE pro-on regional impacts that seeks to develop a model designed to capture the essential climate-sensitive relationships within and between resource sectors (6).

Research that MARS classified as focused on economics received $1.0 million in FY 1992; no research was classified as focused on social dynamics.

Research "Contributing" to Adaptation

MARS identified research on the effects of climate change on natural and engineered systems and research on the potential impact on society of these changes as contributing to adaptation research. With the exception of NASA's component, the majority of USGCRP research under the science elements Ecological Systems and Dynamics and Human Interactions can be considered impacts research-that is, how climate change effects plants, animals, and people. Ecological Systems and Dynamics research made up $224 million, or 17 percent, of the FY 1993 USGCRP budget, and Human Interactions research made up $22 million, or less than 2 percent of the USGCRP budget. NASA spent 66 percent

Table 3-4A-Percent of Total FY 1992 USGCRP Budget for the Third Science Element, Ecological Systems and Dynamics (ESD), Compared with Percent of Each Agency's GCRP Budget for ESD[a]

Agency	Percent of USGCRP ESD budget allocated or requested[b]		Percent of USGCRP ESD budget allocated or requested as percent of each agency's GCRP budget	
	FY 1993	FY 1994	FY 1993	FY 1994
DOC/NOAA	1	1	5	4
DOD	<1	<1	15	15
DOE	2	2	4	4
DOI	4	3	21	24
EPA	4	4	36	39
HHS	0	0	0	0
NASA[c]	66	66	16	16
NSF	10	12	17	18
Smithsonian	2	2	62	62
TVA	0	0	0	0
USDA	11	10	53	52

[a] ESD received $224.3 million in FY 1993; for FY 1994, the budget request is for $249.3 million (approximately 17 percent of the total USGCRP budget).
[b] FY 1993 figures represent appropriated funds; FY 1994 figures represent requested funds.
[c] Part of the reason the NASA figures are so high is that the capital costs of their projects are greater relative to other projects. Although these comparisons are instructive, they do not reflect information on the cost and yield of research.

Table 3-45-Percent of Total FY 1992 USGCRP Budget for the Fifth Science Element, Human Interactions (Hi), Compared with Percent of Each Agency's GCRP Budget for HI[a]

Agency	Percent of USGCRP HI budget allocated or requested		Percent of USGCRP HI budget allocated or requested as percent of each agency's GCRP budget	
	FY 1993	FY 1994	FY 1993	FY 1994
DOC/NOAA	3	3	1	1
DOD	0	0	0	0
DOE	11	10	3	3
DOI	13	6	7	4
EPA	15	11	13	10
HHS	5	6	100	100
NASA	0	0	0	0
NSF	42	53	8	8
Smithsonian	3	3	10	10
TVA	0	0	0	0
USDA	8	9	3	4

[a] HI received $22.2 million in FY 1993; for FY 1994, the budget request is for $24.4 million (approximately 1.6 percent of the total USGCRP budget).
[b] FY 1993 figures represent appropriated funds; FY 1994 figures represent requested funds.
SOURCE: Office of Technology Assessment, 1993.

of the total USGCRP Ecological Systems and Dynamics budget; however, Ecological Systems and Dynamics research represents only 16 percent of the agency's global change research budget (see table 3-4A). In addition, NASA's research in this area focuses primarily on ecologi- *malfunctions* and *characterizations,* not *effects of* climate change on ecological systems. In contrast, USDA spends only 11 percent of the USGCRP Ecological Systems and Dynamics budget, which represents 53 percent of their global change research budget. DOI spends 3.5 percent of the USGCRP Ecological Systems and Dynamics budget, which represents 21 percent of their global change research budget (see table 3-4A). The agencies that one would expect to conduct the bulk of research on ecological systems and the effects of climate change on ecosystems--EPA and the land-management agencies of DOI and USDA-play only a minor role. The reasons are varied and complex, but include the higher capital costs of NASA projects and the reluctance of some agencies to actively support and participate in the program. Consequently, these agencies' contributions to USGCRP comprise projects that are in place for reasons other than climate change research, such as characterizingg ground- and surface-water flows, maintaining weather data, and monitoring ecosystem change.

Definitions of what encompasses Ecological Systems and Dynamics research become very important in the face of such disparate budget allocations among agencies. If the definition is not consistent across agencies, or if it is too broad, large gaps could potentially exist. For example, it is unclear how much large ecosystem research is being conducted-such as research on the use of corridors for the migration of plants and animals in response to global change or techniques for ecosystem transplantation. Are we clarifying rates at which various species in an ecosystem can migrate? Do we understand how to maintain ecosystems in place? Will pest ranges increase? Will fire hazards increase? Are our crop and tree varieties genetically diverse enough to cope with the range of potential changes? What agencies are addressing these questions, and is research adequate to find the answers to these questions? What questions under this research category does NASA attempt to answer compared with what questions USDA attempts to answer? NASA's contribution to the understanding of ecological systems comes largely from space-based measurements and observations, whereas the land-management agencies' contribution comes more from field research. Box 3-B highlights weaknesses in environmental research identified by the National Research Council (NRC).

Of the $22 million spent on Human Interactions, NSF spends 42 percent, which represents 7.5 percent of their global change research budget. Except for the Department of Health and Human Services (HHS), which spends $5.41 million, or 100 percent, of its USGCRP budget on Human Interactions, the percent of agency USGCRP budgets allocated to Human Interactions ranges from O to 10 percent (see tables 3-3B and 3-4B). Although it is difficult to obtain reliable numbers, because social science research has many labels, it is doubtful that any Federal agency devotes as much as 1 percent of its total research budget to environmental social science (37).

Specific projects classified as contributing to adaptation include: a $4.7 million program at DOI's National Park Service (NPS) to improve the scientific basis of adaptive management of the types of ecosystem responses likely to be associated with climate and other global environmental changes; a $1.3 million program at DOI'S Bureau of Reclamation (BOR) to study the changes in hydrologic processes under scenarios of global climate change and to determine the potential impacts on snowpack, snowmelt, and runoff in the 17 Western States; a $1.5 million program at DOI'S U.S. Geological Survey (USGS) to evaluate the sensitivity of water resources to climate variability and change across the United States; and a $150,000 DOE program to evaluate the existing social science knowledge base concerning energy and the analysis of the role of institutions in making decisions affecting climate change (6).

Very little of the effects research described above could also be considered research on the impacts of global change on human systems. USGCRP'S new Economics Initiative does consider the impact of climate change on the economy, and several agencies support research in this area, including NSF, NOAA, and USDA (in its Economics Research Service). However, the eco-

Box 3-B–Weaknesses in U.S. Environmental Research Identified by the National Research Council

- The research establishment **is poorly structured to deal with** complex, interdisciplinary research **on large** spatial scales and long-term temporal scales. These traits characterize the primary needs of an effective environmental research program.
- There is no comprehensive national environmental research plan to coordinate the efforts of the more than 20 agencies involved in environmental programs. Moreover, no agency has the mission to develop such a plan, nor is any existing agency able to coordinate and oversee a national environmental research plan if one were developed.
- **The lack of an integrated** national research plan weakens the ability of the United States to work creatively with governments of other nations to solve regional and global problems.
- The Nation's environmental efforts have no dear leadership. As suggested by the lack of a cabinet-level environmental agency, the United States has lacked strong commitment to environmental research at the highest levels of government. Environmental matters have been regarded as **less** important than defense, health, transportation, and other government functions.
- Although individual **agencies** and associations of agencies analyze data to provide a base for **decisions** on strategies and actions to address specific environmental problems, no comprehensive **"think** tank" exists for assessing data to support understanding of the environment as a whole and the modeling of trends whose understanding might help to set priorities for research and action.
- Bridges between policy, management, and science are weak, There is no organized system whereby assessments of environmental problems can be communicated to **decisionmakers** and policy-setters.
- Long-term monitoring and assessment of environmental trends and of the consequences of environmental **rules** and regulations are seriously inadequate. The **United** States has a poor **understanding** of its biological resources and how they are being affected by human activities. Although biological surveys have a long history at the State and Federal level in the United States, it is only very recently that we appear to be approaching a consensus on the need for a comprehensive, national biological survey.
- There Is **insufficient** attention to the collection and management of the vast **amount** of data being developed by the 20 agencies involved in environmental research. **Collection** and management **of environmental life-science** data are **less well** organized than those of environmental **physical-science** data.
- Education and training in the Nation's universities are **still strongly** disciplinary, whereas **solution** of environmental problems requires broadly trained people and **multidisciplinary** approaches. Opportunities for **broadly** based **interdisciplinary** graduate degrees are few, and **faculty** are not rewarded as **strongly** for interdisciplinary activities as they are for disciplinary activities Thus, there is a risk that **environmental** scientists appropriately trained to address pressing needs will be lacking.
- **Biological-science** and social-science components of environmental research are **poorly** supported, compared with the **(still** inadequate) support given to the **physical** sciences.
- Research on engineering **solutions** to **environmental** problems is **seriously** underfunded. That reduces our ability to protect ecosystems and restore damaged ones to productivity and jeopardizes the Nation's ability to achieve **major economic** benefits that are certain to derive **from** increasing **worldwide** use of technologies for these purposes.
- With respect to environmental affairs, government operates in a **strongly** adversarial relationship with both industry and the general **public, to** the detriment of integrated planning and maintenance of an atmosphere of **mutual** trust that is **essential** for effective government functioning.
- With important exceptions in the National Science Foundation, the National Oceanic and Atmospheric Administration, and the US. **Geological** Survey, most environmental research and development is narrow, supporting either a regulatory or a management function. That appears to be particularity true in the environmental **life** sciences.

SOURCE: National **Research** Council, ***Research to Protect, Restore, and Manage the Environment,*** **Committee on Environmental Research, Commission on Life Sciences (Washington, DC: National Academy Press, 1993).**

nomics component of USGCRP is not well-integrated with the rest of the program.[21]

CEES is aware of the absence of research on the impacts of climate change and has slightly expanded Earth Process Research, the second integrating priority, to include research to determine the impacts associated with predicted global changes (12). However, explicit recognition of the need for research on impacts of climate change is not yet reflected in the program structure.

A New Adaptation Program

For reasons discussed above, it is necessary to pursue research on impacts of global change and potential response and adaptation strategies without waiting for USGCRP to complete climate research. The issues addressed by MARS continue to be discussed because MARS sought to answer near-term policy questions and questions that naturally accompany climate change research: If the climate is changing, how will forests, agriculture, and natural areas be affected and what should we do? MARS may not have had the administrative, congressional, and program support it needed to pursue its mission a few years ago, but now MARS-related questions are being asked with more persistence, and it might be time to consider reinstating another MARS-type program.[22] The following discussion addresses how such a program might be structured. We suggest some possible ways to incorporate adaptation into USGCRP below and in option 3-5.

A framework for developing research priorities for an adaptation research program (ARP) should be developed through a combination of an interagency committee and an external advisory panel. The interagency committee should consist of members from several scientific disciplines and the policy- and decisionmaking communities. Committee and advisory panel members should be committed to the goal of creating a management- and policy-relevant research program.

The committee and advisory panel could address the following questions:

1. What areas of science are important to pursue in order to support adaptation research? What existing federally supported research, which is not currently classified as global change research, could be augmented to support an adaptation-focused research program?
2. What areas of research would most effectively reduce the physical, biological, social-behavioral, and economic uncertainties faced by decisionmakers in choosing among policy options affecting global change?[23]
3. How can ARP be organized so that it is useful to public and private decisionmakers?

Answers to these questions require cooperation and coordination in the ecological and social sciences communities, coordination among the land-management agencies, and a clear delineation of the role of adaptation research in agency policy and management. As concluded by the Committee on Human Dimensions of Global Change, there is "an almost complete mismatch between the roster of Federal agencies that support research on global change and the roster of agencies with strong capabilities in social science" (35). There is a similar mismatch between the roster of Federal agencies with environmental responsibilities and the roster of agencies with strong capabilities in social science (37).

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21 OTA's workshop "EOS and USGCRP: Are We Asking and Answering the Right Questions?" Washington, DC, Feb. 25-26, 1993.

22 Congress specifically asked OTA t. address adaptation issues; however, if Congress chooses to instigate an adaptation program, it should also decide whether related mitigation issues should be addressed along with an adaptation program, as a separate program, or within USGCRP.

23 This question was developed in the National Acid Precipitation Assessment Program's (NAPAP's) 1984 annual report for Task Group I (39). Unfortunately, that task group was disbanded the next year.

The Ecological Society of America's Sustainable Biosphere Initiative (SBI) has made a start in fostering cooperation among the ecological and social sciences. SBI has clearly laid out scientific priorities in the ecological sciences. Coordination among the land-management agencies is also beginning with groups such as the Terrestrial Research Interest Group, an ad hoc coordinating committee of Federal agencies and other organizations conducting terrestrial research (see box 5-J). An adaptation program could continue to encourage such efforts.

Budget Mechanisms for ARP

Because the scope of any ARP would reach across agencies, a new agency or executive body, or a new office in an existing agency, could be created to house it or, as with USGCRP, a budget crosscut could be used. Because several agencies have significant expertise and infrastructure to pursue research on adaptation to global change and because of budget constraints, Congress might find it difficult to create a separate body for ARP. If an existing agency housed ARP, it could undermin e the ARP mission by creating tension among agencies about interagency authority. Because budget crosscuts have worked weIl in the past, at least until the point when they are submitted to Congress, the use of a budget crosscut for ARP might be desirable.

FCCSET currently coordinates the budget crosscut of USGCRP and could coordinate the budget crosscut for ARP. However, because FCCSET supports science, engineering, and technology initiatives but does not initiate management- and policy-relevant deliberations within these programs, it may not be the best organization for ARP budget coordination. If an office within the White House coordinated ARP's budget, the program could more easily maintain its emphasis on policy-relevant research; however, it might be more subject to political pressure.

ARP WithIn USGCRP

If Congress does not wish to create anew ARP, but chooses instead to augment the existing USGCRP three points should be considered. First, the priorities of USGCRP would need to be changed. In addition to observation, understanding, and prediction, "planning' for climate change and other global changes, including adaptation, would have to be incorporated into the USGCRP goals. The seven scientific elements in the priority structure of USGCRP might need to be rewritten, with the help of advisory panels, agency personnel, and, perhaps, the National Research Council. More funds would need to be allocated to the research topics under the present Ecological Systems and Dynamics and Human Dimensions elements. Adaptation would have to be incorporated into the existing elements, or a new adaptation element would have to be added.

Second, as would be the case with a separate program for adaptation, the land-management agencies must be encouraged to unify their research programs that address ecological and human-system response to and management of global change. Congress must commit more resources to the Ecological Systems and Dynamics and Human Interactions research areas, especially within the land-management agencies. Finally, projects currently supported under USGCRP would need to be reviewed for their usefulness to adaptation research. For example, the Earth Observing System (EOS) currently concentrates on climate monitoring and ecological monitoring, primarily for the sake of determining land-atmosphere interfaces for global climate models. Could EOS be modified to provide information on processes that are important for adaptation?

EVALUATION MECHANISMS

To date, there has been no formal evaluation of the overall scope, goals, and priorities of USGCRP and of whether its activities collectively are addressing the needs of policy makers.

Several evaluation mechanisms could be used to address the dichotomy between science and policy in USGCRP, including internal and external reviews, integrated assessments, and coordinated congressional oversight. Appropriate communication links among scientific disciplines, Federal agencies, State agencies, policy makers, decisionmakers, and all levels of USGCRP are vital for its success.

Reviews

Most formal reviews of USGCRP elements have centered on the instruments and methods used in research about specific scientific priorities or have focused on individual projects within the program. For example, teams reviewing the EOS program have addressed specific instruments that EOS should use, and the National Academy of Sciences (NAS) has carried out reviews and midcourse evaluations of specific agency programs and projects.

Reviews should be used as a mechanism for maintaining flexibility in the program and to redirect its activities, if necessary. Reviews should: be timely and efficient; include people who do not have an immediate stake in USGCRP, but do have significant knowledge about its current structure, content, and history; be conducted periodically to reflect the nature of the questions being asked; and identify programs that can be eliminated as well as recommend new ones. Perhaps most importantly, reviews that call for a redirection in the overall program should consider that research on global change issues requires a financial and institutional commitment that transcends political and budgetary cycles. Reviews should not be used to respond to the political crisis of the day or as a mechanism to undermine effective programs with long time horizons.

Integrated Assessments

Reviews generally look at individual parts of a program or the program as a whole and determine how they are functioning; they do not try to integrate the program's different research results. Integrated assessments are a mechanism for synthesizing all the research relevant to an identified problem and for presenting research results in a policy context to decisionmakers (13, 42).[24] Just as important, integrated assessments help guide research and identify key assumptions, uncertainties, gaps, and areas of agreement. The Federal Government tried to incorporate an assessment process into the National Acid Precipitation Assessment Program (NAPAP) in the 1980s with only limited success (see box 3-C). A challenge for the global change research community will be to devise assessments that minimum disruption of ongoing programs but still allow for redirection of program elements in light of new discoveries, advances in technology, and changing long-term needs of policy makers.

Scientific information is critical, but not sufficient, in determining how the United States should respond to the risks of global change. If USGCRP is to be driven by social relevance as well as by scientific curiosity, its research priorities should include sociocultural factors as well as physical factors (23). Integrated assessments could help determine the importance of the problems presented by global change relative to other policy problems, outline alternative policies to respond to global change, and explain the pros and cons of various responses and implementation strategies.

For example, preliminary results of an integrated assessment computer model to prioritize policy-relevant research, by Carnegie Mellon University, suggest that: economic and ecological impacts are unambiguously the most important

[24] *Integrated assessment* (also known *as comprehensive* and end-to-end *assessment*) *is* an *evolving* concept. An integrated assessment of global change would generally include at least the following activities: assessments of the physical science component of a project; assessments of the potential impacts of change on the environment, human heal@ and the economy; assessments of the effectiveness and economic impact of possible societal responses to change; and assessments of the political feasibility of possible responses (31),

Box 3-C-Lessons from NAPAP

In 1980, Congress passed the Acid Precipitation Act (Title VII of the Energy Security Act, P.L. 96-294) and thereby established an interagency task force to plan and oversee a 10-year National Acid Precipitation Assessment Plan (NAPAP). The National Oceanic and Atmospheric Administration, the U.S. Department of Agriculture, and the Environmental Protection Agency jointly chaired the task force, which included representatives from the Department of the Interior, the Department of Health and Human Services, the Department of Commerce, the Department of Energy, the Department of State, the National Aeronautics and Space Administration, the Council on Environmental Quality, the National Science Foundation, and the Tennessee Valley Authority along with representatives of the Argonne, Brookhaven, Oak Ridge, and Pacific Northwest National Laboratories and four Presidential appointees. The purpose of NAPAP was to increase our understanding of t he causes and effects of acid precipitation through research, monitoring, and assessment activities that emphasized the timely development of science for use in decisionmaking (39).

NAPAP (with an annual budget that ranged from about$17 million at the beginning of the program to just over $300 million at its end) was one of the most ambitious interagency programs ever focused on a particular problem (47). It was designed to be a major research effort that provided policy-relevant information in a timely manner. It succeeded in its research efforts, but it did not provide policy-relevant information in a timely manner. Because the nature of problems facing the country is increasingly interdisciplinary and global in scope, it is reasonable to assume that the government will mandate more programs that try to bridge the gap between science and public policy. To reap the greatest benefits from t hese programs, it will be necessary to incorporate the lessons of NAPAP into program structure. This box focuses on the Task Group on Assessments and Policy Analysis and the overall lessons learned from such a large, interagency program.

When founded, NAPAP consisted of 10 task groups, each with a single agency serving as the coordination contact: Natural Sources of Acid Precipitation, Human Sources of Acid Precipitation, Atmospheric Processes, Deposition Monitoring, Aquatic Effects, Terrestrial Effects, Effects on Materials and Cultural Resources, Control Technologies, Assessments and Policy Analysis, and International Activities. In 1985, the assessments and policy analysis task group was disbanded-a decision that undermined the value of the program for decisionmakers.

Congress established NAPAP in large part to determine whether acid rain was a problem. However, in the context of research NAPAP did not approach acid rain as a unified issue. Rather, it examined the subject at multidisciplinary and subdisciplinary levels with little emphasis on synthesizing findings. As stated in one critique (24):

> The program reported findings in excruciating disciplinary detail, an approach which was not especially helpful to non-specialist decision makers. The disciplinary pluralism of NAPAP also allowed policy advocates to pick and choose among NAPAP's reported findings, emphasizing facts or uncertainties supporting a particular position and deemphasizing others. NAPAP lacked an extra-disciplinary perspective that would have allowed it to characterize acid rain as a problem, non-problem, or something in between.

Assessment and policy analysis research develops and uses quantitative methods to organize and communicate scientific and other information in ways that allow comparison of policy choices. These methods include decision analysis, benefit-cost analysis, risk analysis, and technology assessments. The NAPAP Task Group on Assessments and Policy Analysis attempted to begin early in the program to develop integrated assessment methodologies and to perform multiple assessments throughout the program to ensure policy relevance. A 1985 report was to include an assessment of the current damages attributed to aad deposition, an uncertainty analysis of key scientific areas, and the implications of uncertainty for policy choices. The task grwp also tried to develop a framework for the methodology for subsequent integrated assessments in 1987 and 1989 (25).

(Continued on next page)

Box 3-C-Lessons from NAPAP—(Continued)

However, in 1985, NAPAP's management changed and, consequently, the focus of the program changed. The assessments task group was disbanded, and responsibility for assessments was transferred to NAPAP's director of research. It was uncertain whether NAPAP would produce even one assessment: NAPAP ceased funding integrated assessment modeling because the Interagency Scientific Committee decided to spend their limited funding on other research. The new director repeatedly delayed the 1985 assessment, but it was finally released-with much controversy-in 1987. The 1987 and 1989 integrated assessments were never produced. Finally, during the last few years of the program, NAPAP produce its second integrated assessment; however, the 1990 publication of the report came too late to be of maximum use to policy makers in formulating the amendments to the Clean Air Act (47).

Because NAPAP failed to carry out the full range of assessments it originality planned, key components for the 1990 integrated assessment were either not pursued or were underfunded, and the assessment was incomplete (39). For example, although NAPAP was initially supposed to evaluate the economic effects of acid deposition on crops, forests, fisheries, and recreational and aesthetic resources and to determine the implications of alternative policies, funds were significantly reduced for research in these areas (47).

The Oversight Review Board (ORB) of NAPAP, in its 1991 report to the Joint Chairs Council of the Interagency Task Force on Acidic Deposition, strongly emphasized that an assessment function be given primacy throughout an interagency program (39). ORB's key recommendation on lessons learned about the interface between science and policy was to give assessment priority over research (24) because "science and research findings *per se* have little to offer directly to the public policy process, [and] their usefulness depends on assessment, defined as the interpretation of findings relevant to decisions" (39). ORB also outlined eight other suggestions that any program with such a close interface between science and policy should follow:

1. Match institutional remedies to problems.
2. Obtain and maintain political commitment.
3. Take steps to ensure continuity.
4. Configure organization and authority to match responsibility.
5. Give assessment primacy.
6. Provide for independent external programmatic oversight.
7. Understand the role of science and how to use it.
8. Take special care with communication.
9. Prepare early for ending the program.

The insights gained from the experiences of NAPAP were not considered when designing the U.S. Global Change Research Program (USGCRP)—a much larger program on both a temporal and spatial scale than NAPAP. Some argue that USGCRP is following the same path as NAPAP—good research will come from USGCRP, but the results will not be used to inform policy, and decisions concerning global change will be made with little more knowledge than is available today (42). The logical questions to ask are: Why didn't Congress use the experiences of NAPAP in formulating legislation for USGCRP, and how should incorporation of lessons from NAPAP be integrated into USGCRP and future interagency programs?

SOURCE: Office of Technology Assessment, 1993.

sources of uncertainty and that reducing the uncertainty is more important than resolving the differences among climate models; the priority placed on research in different fields will vary according to the policy objectives chosen and the time horizon; although they must not be ignored, uncertainties about climate variables appear, in many cases, to be less important than certain social, economic, **and ecological factors; and models** that measure all **impacts in** monetary terms are unlikely to be able to explore many of the most important aspects of the climate problem (15).

Regardless of the scope of an integrated assessment, its **primary functions should be:** to **identify key questions** to **be answered, to survey the state of** current scientific judgments about what we know and do not know about global change and its impacts, to idenify and prioritize what the key uncertainties are in relation to policy needs, to list key assumptions and judgments, to idenify **where** new **research** is needed to aid the **policy process** most **effectively, including** research on **key uncertainties in understanding the climate system and fostering mitigation and adaptation research, and** to **establish the** requirements for peer and public review (24, 42).

Assessments need not be conducted sequentially (e.g., results of earth science research or economic research need not be complete before an assessment can begin), but should begin at the beginning of a program and continue throughout the life of the program (l). The ideal assessment would pay particular attention to bridging gaps and maintainingg essential links among various research projects and disciplines and would determine the value of new information.

The Massachusetts Institute of Technology, Carnegie Mellon University, the Electric Power Research Institute, and Battelle Pacific Northwest Laboratory have programs for developing computer models for integrated assessments. For example, the Battelle Pacific Northwest Laboratory is developing an Integrated Climate Change Assessment Model (ICCAM)[25] that will incorporate information from models on human activities, atmospheric composition, climate and sea level, and terrestrial ecosystems (17). ICCAM is intended to be an integrated collection of these **models in** a reduced, or simplified, form, with the goal of giving practical answers to practical questions. The models are limited by the complexity and uncertainty of each system, and some fear that the results from these integrated assessments could be difficult to understand. However, these models can at least help to structure thought, direct inquiries, identify which uncertainties are important and which are not, and suggest courses of action (40).

Assessments could be performed by independent, nongovernment committees, Federal interagency task forces consisting of agency personnel who are participating in the program, a mix of the two groups, or by the National Academy of Sciences (42). Nongovernment committees would offer the fresh perspective of independent evaluators who are less weighed down by political agendas; however, they might have little control over the agencies they are trying to influence. Interagency committees would have the advantage of using Government researchers who are well-informed about the program and who could not easily ignore assessment findings.

To date, integrated assessments have received little administrative support and almost no funding from any ongoing program. Some agency personnel have expressed interest in integrated assessments, but few have committed any resources to it (EPA and DOE have funded some assessment research). The little funding that integrated assessments have received has come largely from NSF and the Electric Power Research Institute. A small percentage of the total USGCRP budget—perhaps 1 to 5 percent-could be set aside for integrated assessment (15, 50). The Carnegie Commission also recommends that a larger percentage of environmental research and development dollars go toward assessment and **policy research (4).**

[25] Battelle Pacific Northwest Laboratory is working in conjunction with the University Corporation for Atmospheric Research, the Electric Power Research Institute, the U.S. Department of Energy, and the Environmental Protection Agency.

Congressional Oversight

Congress has held several hearings on global climate change that have focused predominantly on what we know, what we do not know, the accuracy of current data, reconciling the existence of conflicting data, the implication of climate change for natural resources and the economy, and the potential costs of actions designed to mitigate climate change. However, these hearings have not successfully addressed USGCRP as a program. Some hearings have focused on the current research of program participants, which is a first step in determiningg the necessity of the research, but few have focused on whether USGCRP research was supplying information needed to develop policy responses to global change. The direction of the program and its emphasis on the first two science elements have not been altered.

In addition, the different committees with jurisdiction over USGCRP have not been equally active in their oversight activities. As a result, certain portions of the program are regularly reviewed while others are never reviewed.

New approaches to traditional authorization and appropriation procedures for large interagency programs such as the USGCRP need to be considered. The current authorization and appropriation process guarantees that USGCRP will be examined by Congress only in pieces (38). An annual, ad hoc appropriation subcommittee might be created to specifically address the USGCRP budget as a whole. This committee should consist of members from appropriation subcommittees with jurisdiction over elements of USGCRP (see table 3-2).

For congressional oversight to be effective in influencing USGCRP, a long-term systematic approach to communication and oversight must be developed. Congressional feedback, expectations, and prospective actions must be communicated quickly to the program. Oversight should be extended to include regular meetings among policy makers who have jurisdiction over USGCRP and USGCRP participants; an interdisciplinary, multiagency group working with USGCRP; and outside reviewers. Results from these meetings should be freely and widely disseminated. Oversight hearings should be coordinated with all committees who have jurisdiction over USGCRP (see table 3-l).

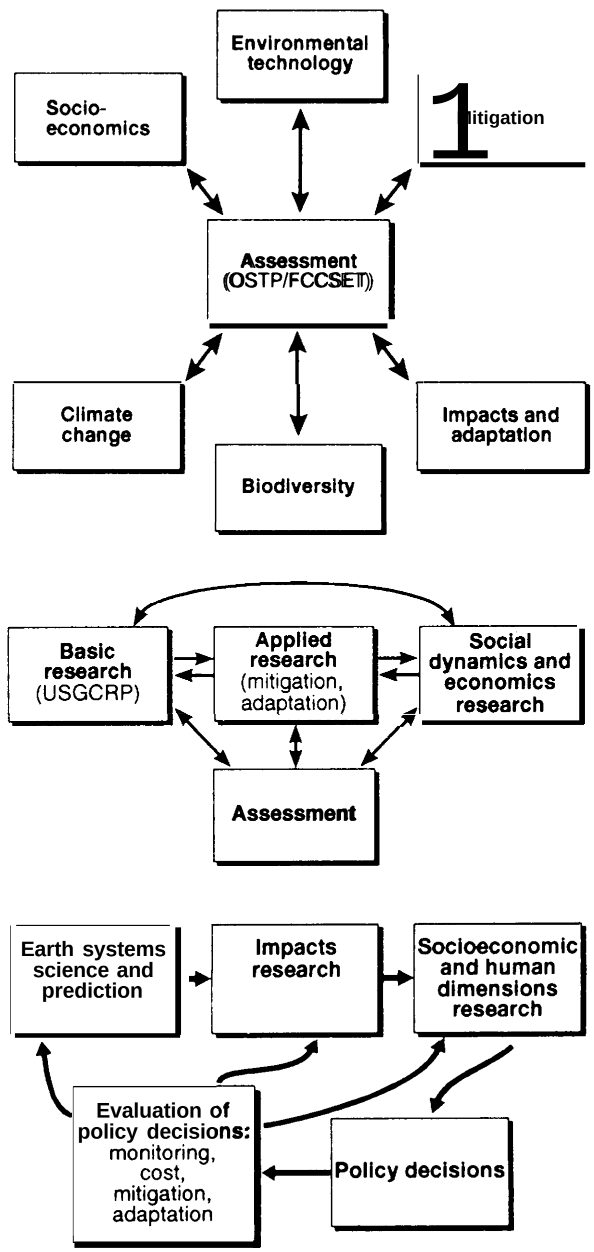
POLICY OPTIONS: AUGMENTING THE FEDERAL RESEARCH EFFORT ON GLOBAL CHANGE

To policy makers, climate change does not become a problem the moment that the change in the Earth's mean average temperature becomes statistically significant. For them, it becomes a problem when a community feels the pinch of an unwanted event-drought or flood or decline of timberland, for example. Knowing how best to ameliorate or cope with any costs that climate change might induce is important to policy makers. Knowing how mitigation efforts to re duce greenhouse gases will affect our ability to adapt is important. Knowing what information is knowable and unknowable over various time scales is important to policy makers. This kind of information does not automatically emerge from a basic research program. To be useful to the governing bodies of the world, the science facts gained by USGCRP must somehow be translated into potential costs or benefits incurred by climate change and must guide strategies to prepare for or react to change. Currently, there is no formal mechanism in USGCRP for making the link between policy and science.

Given the complicated and long-term nature of climate change, the research needed to understand it, and the shorter-term needs of policy makers, a research program for global change should ideally:

- identify the key science and policy questions for the near term and the long term;
- orchestrate a research program that involves the physical, biological, and social scientists;

Figure 3-8-Alternative Organizational Schemes for Global Change Research



SOURCE: Office of Technology Assessment, 1993.

- integrate the research results across disciplines (i.e., assess the state of understanding) periodically; and
- communicate results back to the researchers and policy makers effectively.

Identifying the outcomes that matter to policy makers should be the first step in refining global change research programs, with scientists helping the policy makers to ask pertinent questions (14). Next, scientific priorities should be compared with the policy questions. Where there are serious mismatches between scientific and political priorities, programs should be reevaluated-not to direct a basic science agenda, but to ensure that key information needed for policy decisions from many disciplines is available alongside the fundamental chemistry and modeling. The particular disciplines, research methods, and instruments that would be used to gather and analyze data should flow from these priorities and should be science-driven. Ideally, information needs of decisionmakers will influence questions asked by scientific researchers, and vice-versa. For example, the communication between scientists and policy makers may cause a change in key policy questions, which in turn may redirect the research program; "policy makers need to understand the limitations of what science can determine, and scientists must understand what the policy community really needs' (42). This has proved difficult in past research efforts, such as NAPAP's (See box 3-C).

The following policy options generally fall under three categories:

- Effectively broaden USGCRP by incorporating results of Federal research relevant to but not currently under its purview. USGCRP as currently constructed and implemented cannot do this. It could require congressional or executive branch codification. There are several policy options directed both at broadening USGCRP and at ensuring that USGCRP and other programs relevant to global change are connected (the diagrams in fig. 3-8 show some possible organizational schemes for building in some of the missing components). The National

Research Council has recommended the creation of a National Environmental Council in the Executive Office of the President (37), and the National Commission on the Environment (NCE) recommended the development of a National Environmental Strategy (34); either or both of these could complement the options described below.

- Increase funding or redirect funding to areas where research is inadequate. A modest redirection of 1 to 5 percent of current funding ($15 to $70 million) could begin filling in the large gaps between the current climate change program and a policy-relevant global change program (15, 50). Because the bulk of this OTA report focuses on natural-resource-based systems and the Nation's potential to adapt to climate change, we discuss coordinating existing ecosystem research and initiating new efforts that are critical to planning for and/or managing natural resources under climate change. However, building strong socioeconomic components of USGCRP is equally important.
- Make the program more relevant to policy making by incorporating an assessment function. Assessment and regular reevaluation of USGCRP could be instrumental in identifying the current information base on climate change, gaps in knowledge, and short- and long-term policy questions.

Effectively Broaden USGCRP

As currently structured, USGCRP is a collection of programs from several agencies with no central management. Although research should remain decentralized, coordination should be centralized and top-down. The Subcommittee on Global Change Research under the Committee on Earth and Environmental Sciences is currently responsible for coordinating activities under the Federal Coordinating Council for Science, Engineering, and Technology. FCCSET acts largely as a fulcrum for coordination, but agency participation in FCCSET projects is voluntary, and FCCSET has no authority over how participating agencies spend their funds. A previous OTA report (48) looked broadly at the health of U.S. research and development and concluded:

> In the Executive Branch, Congress should insist, at a minimum, on iterative planning that results in: a) making tradeoffs among research goals; and b) applying (after scientific merit and program relevance) other criteria to research decisionmaking that reflects planning for the future. . . OSTP [Office of Science and Techhnology Policy] could initiate broader priority-setting.

Option 3-1: *Amend the* ***Science Policy*** *Act of* **1976** ***(PL.*** **94-282),** *which established the Office of Science and Technology Policy* ***and the Federal*** *Coordinating Council on Science, Engineering, and Technology, to strengthen the ability of these offices to coordinate science and* ***ecosystem*** *management across agencies. OSTP was established* to "define coherent approaches for applying science and technology to critical and emerging national and international problems and for promoting coordination of the scientific and technological responsibilities and programs of the Federal departments and agencies in the resolution of such problems," and FCCSET was established to "provide more effective planning and administration of Federal scientific, engineering, and technological programs" (P.L. 94-282). These offices have the authority to develop and implement coherent, Government-wide science policy and have been the mechanism for coordinating several multiagency programs. However, OSTP has not always been an active or influential player in the executive branch, and FCCSET lacks the authority to set priorities, direct policy, and fully participate in the budget process (2, 21). The directions for environmental research must be set-and responsibilities among various Federal agencies must be coordinated-at the executive level because environmental research is of the highest national importance.

About 20 Federal agencies have major responsibilities related to the environment. In all instances (except for EPA), concern for the environment is not the primary role of the agency conducting the environmental research (37). For example, DOE supports much environmental research, but the department's primary responsibility is energy, not the environment.

OSTP could be given budgetary authority, perhaps in conjunction with the Office of Management and Budget, to guide agency programs that contribute to science and technology. This could mean reinstating "fencing," or requiring agencies to commit funds to USGCRP projects (see footnote 12). These funds could not then be redirected to meet OMB targets for other areas within each agency.

A further step would be to create a National Science and Technology Council to replace FCCSET as proposed by Vice President Gore in his National Performance Review (21). Under this plan, agencies would clear their budgets with the science council as well as with OMB.

Option 3-2: *Establish a committee within FCCSET to standardize the criteria for classifying focused and contributing research to USGCRP and to classify all government research accordingly.* Much research that could qualify as "contributing' to USGCRP may be ongoing under another title (such as "Environmental Biology;' see option 3-6 below). Likewise, more "focused work" might occur in the agencies if the USGCRP scope is broadened. A defined set of criteria for classifying research would be of great value in identifying Federal research that is truly pertinent to the global change problem and in identifying critical gaps in research.

option 3-3: *Reassess program priorities.* Reassess the order of priority given to the seven science elements. Although the current structure is producing good science, research results will not be sufficient to provide the information necessary to answer policy questions concerning the impacts of climate change on the Nation's resources. To answer these questions, more emphasis needs to be directed toward the science elements that address the ecological, socio economic, adaptation, mitigation, and human aspects of global change. Some of this can be done easily within the current construct of USGCRP; some may require additional programs outside the USGCRP research structure.

Option 3-4: *Make research on the human dimensions of global change a primary element of the program.* A human-dimensions program would look at the interface between human actions and the natural environment. Humans alter the environment through population growth, economic growth, technological change, political and economic institutions, and attitudes and beliefs. Human response to a changing environment will depend on individual perceptions, markets, sociocultural systems, organized responses at a subnational level, national policies, international cooperation, and global social change (35). These elements of a human-environment interface will directly influence adaptation responses to climate change.

Option 3-5: *Create an adaptation and mitigation research program (ARP) either within USGCRP or separate but parallel to it. This* program should either have the authority to influence project selection throughout USGCRP or feed into a formal assessment process that influences program direction. Congress must decide whether an ARP should function as a program separate from, but parallel, to USGCRP or whether ARP should operate within USGCRP. If ARP is created as a separate program, it should have formal ties to USGCRP. If USGCRP subsumes adaptation, the USGCRP mission would have to change to make adaptation equal in importance to the other three activity streams.

The mission of such a program must explicitly state its management and policy orientation. ARP's mission might be:

> . . .to pursue research that will support public and private decisionmaking on issues related to global change if climate change occurs. At a minimum,

research will include studies of the public and private management of natural and managed systems and of how to develop strategies to adapt to the effects of climate change. Annually, the program will assess the state-of-the-science, develop Government policy and management options for responding to the potential for global change (including programs that supply information to private decisionmakers), and incorporate these findings into new research directions. The assessment, policy options, and new directions for research will be reported to Congress in an annual report presented along with the President's Budget Request.

The program must include a formal mechanism for bridging the gap between science and policy; specifically, integrated assessments need to be at the center of any ARP structure. Congress should consider mandating this in any enabling legislation in order to ensure that assessments are given top priority.

Congress should consider several "rules of thumb" in structuring the program:

- Management agencies should act as the lead agencies.
- Goals for research must have problem-oriented task descriptions and milestones that are specific and easily measurable.
- Congress should consider retaining the "power of advice and consent' in the appointments of the director and assistant directors of the program.

Other mechanisms for ensuring policy relevance could include requiring the program to make periodic reports to Congress, and giving Congress oversight and investigation authority.

If Congress chose to augment USGCRP, it must recognize that the program has little ability at present to target its programs to help public and private decisionmaking. Given the structure of USGCRP, management- and policy-relevant research would be hard to' initiate because the process of setting priorities in USGCRP is dominated by key agency personnel in conjunction with members of the national and international scientific community.

Incorporate More Ecosystem Research and Natural Resource Planning Into USGCRP

Although an estimated $900 to $943 million is spent on what can be considered research in environmental life sciences (22) or environmental biology,[26] there is currently very little ecological research directed specifically at protecting natural areas under climate change and helping land managers modify management strategies to respond to climate change.[27] Of the $943 million that FCCSET estimates is spent on environmental biology, only 11 percent was also reported as USGCRP program money.[28] A former working group under FCCSET found that in 1992, only $8 million was spent on research focused on adaptation.[29] This number represents less than 0.8 percent of the USGCRP budget and less than 0.9 percent of the amount spent on environmental biology research. A review of ecological experiments from 1980 to 1987 found that 50 percent of all studies were done on very small scales--on plots less than 3 feet in diameter; only 7 percent lasted longer than 5 years. Large-scale and long-term experiments are essential to respond to

26 J. Gosz, Executive Secretary, Subcommittee on Environmental Biology, Committee on Life Sciences and Health, Federal Coordinating Council for Science, Engineering, and Technology, personal communication, Sept. 14, 1993.

27 FCCSET defines *environmental biology as all areas* of biology dealing with the study of @_ and their interactions with their biotic and abiotic environment (J. Gosz, personal communication, Sept. 14, 1993). Gramp et al. (22) define *environmental life sciences as processes and interactions* of living resources such as environmenttal biology, including ecology, forestry, biology, and marine biology.

28 Gosz, op. cit., footnote 26.

29 The Working Group on Mitigation and Adaptation Strategies (disbanded in 1992) of the Committee on Earth and Environmental Sciences of FCCSET identified Federal research that focuses on or contributes to adaptation to global change (6).

the challenges of global research (37). Yet, research on large-scale ecosystem management, structure, and function is necessary to protect natural areas in the future, and it is not clear that it is occurring under the auspices of "environmental biology" or USGCRP.

USGCRP as currently designed will not provide either the practical technologies that might allow us to be more prepared for climate change or the ecological information that would be helpful in providing policy guidance and adaptation options for natural systems.

Option 3-6: *Conduct a review of ecological research within USGCRP and across Federal agencies; evaluate how much long-term ecosystem-level research relevant to climate change, biodiversity, and other long-term problems is under way; and identify important gaps in ecological research.* A review of all research on "natural resources' has not yet been conducted across the Federal agencies. Existing analyses suggest a great deal of money is spent on research relevant to the environment, but how much is useful to understanding long-term ecological problems (such as biodiversity and climate change) is not known. There is currently no mechanism for consolidating results from disparate research efforts into "general patterns and principles that advance the science and are useful for environmental decisionmaking. Without such synthesis studies, it will be impossible for ecology to become the predictive science required by current and future environmental problems" (32).

In volume 2, chapter 5, of this report, we highlight key gaps in our understanding of ecosystems, such as: past climate changes and corresponding species responses, restoration and translocation ecology, the effectiveness of corridors and buffer zones, the development of ecological models, and the effect of elevated CO_2 on assemblages of plants and animals.

Basic research in these areas is needed now to determine how species might respond to climate change and how best to provide for their protection in the future. Agencies could attempt to redirect existing funds within USGCRP or procure new funds for addressing these basic ecological research needs under the Ecological Systems and Dynamics research area. Alternatively, NSF, whose mission is to support basic scientific research, could take the lead in supporting these research areas outside the auspices of USGCRP. The new National Biological Survey (see ch. 1 and vol. 2, ch. 5) could also be an appropriate vehicle to use in addressing some of the research that directly relates to land-management issues.

An effort to characterize and synthesize ongoing research could help bridge the gap between basic research and natural resource planning. Such a review could be conducted by OSTP, NAS, or an independent commission.

Option 3-7: *Make research on monitoring and managing natural resources a key component of a broadened global change research program. One* of the most prudent approaches to natural area conservation under climate change is more coordinated management on the ecosystem or regional scale. This approach would also help address threats to biodiversity and maximize possibilities for species survival under climate change. The land-management agencies should receive increased funding--or existing funds should be redirected-for research that would directly address concerns of managing natural resources under climate change. In particular, as the National Research Council recommends (37), "environmental research should advance the social goals of *protecting the* environment for present and future generations, *restoring* damaged environments so that they are productive once more, and *managing our* natural, economic, cultural, and human resources in ways that encourage the sustainable use of the environmerit. '

Inventory and monitoring programs are usually the last to get funds and the first to be cut in a budget crisis (36, 55); existing institutions are poorly designed to support and strengthen them (37). Many monitoring programs that have been established in protected natural areas have been discontinued because of personnel changes, policy alterations, or budget cuts (55).[30] Baseline information is needed on the status and trends of vegetation cover, plant distributions, animal distributions, soils, and water resources to detect and monitor climate-induced changes. All Federal agencies conduct some type of inventory as a matter of policy, but these efforts vary widely in completeness and quality, are not consistently implemented and funded, and are not coordinated at the national or even agency level.

A concerted effort to connect, in a timely manner, the information contained in inventories to the resource-management and land-use-planning process is vital. If these connections are not adequately addressed, the gap between research and management could increase, which would be detrimental to DOI'S new National Biological Survey.

Incorporate Assessment and Oversight

Option 3-8: *Amend the U.S. Global Change Research Act of 1990 (PL. 101-606) to require periodic integrated assessment reports to be presented to Congress and specify key participants in the assessment process. If* such a program is incorporated into USGCRP, it should be positioned above the agency level. However, because all of the elements necessary for an integrated assessment are not found in USGCRP, an assessment program would have to incorporate information from outside the program and include research that is not formally contained within USGCRP but that contributes to it. An assessment program should fund external and internal assessment efforts. Because integrated assessments that use computer models to knit together all aspects pertinent to global change are not well-developed, they should be used only as a guide to steer program elements. To ensure policy relevance, an assessment program must be given the authority to influence program priorities and project selection. Assessment teams must be interdisciplinary. Documenting the state of scientific knowledge is listed as the primary function of the newly created Assessment Working Group; however, the results of such a survey are highly dependent on the questions being asked-what is regarded as unknown or uncertain depends on what one wants to know and the perspective and background of the person or team carrying out the assessment (24). To ensure commitment and accountability to the assessment process, the director of an assessment program could be appointed with the advice and consent of Congress.

Option 3-9: *Create innovative congressional involvement in USGCRP.* USGCRP does not function as an individual agency, and Congress cannot expect to interact with the program in the same manner it does with agencies. Congress needs to create a forum where USGCRP can be addressed as a whole before being broken down into individual components that fit neatly into authorization and appropriation jurisdictions. For example, the Environmental and Energy Study Institute could conduct an annual seminar for its congressional members on the USGCRP budget, or Congress could establish an ad hoc appropriation committee consisting of members from each committee and appropriations subcommittee with jurisdiction over USGCRP to consider the program's budget as a whole.

Congress should conduct oversight of the program as a whole. Because USGCRP is an interagency program, it cannot be evaluated effectively by Congress on an agency-by-agency basis or through the activities of individual committees working independently. Committees with jurisdiction over USGCRP should coordinate oversight of the program.

[30] For example, in FY 1993, the Bureau of Land Management (BLM) eliminated 6 of its 16 acid rain stations to release about $30,0(K) for other BLM activities. Several of the six stations had been in operation for 10 years and had been maintaining data sets to monitor the health of forests and the effects of acid rain. Continuation of this long-term record was lost as a result of these cuts.

CHAPTER 3 REFERENCES

1. Bernabo, C.J., Science and Policy Associates, Inc., testimony at hearings before the House Committee on Science, Space, and Technology, May 19, 1993.
2. Brown, G.E. Jr., Chairman, Committee on Science, Space, and Technology, U.S. House of Representatives, "Report of the Task Force on the Health of Research, Chairman's Report," Serial L, Committee Print, 1992.
3. Carnegie Commission on Science, Technology and Government, *Enabling the Future: Linking Science and Technology to Societal Goals (Washington DC: Carnegie Co*remission on Science, Technology and Government, September 1992).
4. Carnegie Commission on Science, Technology and Government, *Environmental Research and Development: Strengthening the Federal Infrastructure (Washington DC: Carnegie co*remission on Science, Technology and Government, December 1992).
5. committee on Earth and Environmental Sciences (CEES), Mitigation and Adaptation Research Strategies Working Group, *MARS Working Paper I: Description of Proposed Coordinated Program* (Washington, *DC:* CEES, 1991).
6. Committee on Earth and Environmental Sciences (CEES), Mitigation and Adaptation Research Strategies Working Group, *Directory of Federal Research Activities Related to Mitigation of or Adaptation to Global Change* (Washington, *DC:* CEES, 1992).
7. Committee on Earth and Environmental Sciences (CEES), Our *Changing Planet: The FY 1993 U.S. Global Change Research Program (Washington DC:* CEES, 1992).
8. Committee on Earth and Environmental Sciences (cBES), *Our Changing Planet: The FY 1994 U.S. Global Change Research Program (Washington DC:* CEES, *1993).*
9. *Committee* on Earth Sciences (CBS), Our *Changing Planet: The FY 1990 Research Plan (Washington DC: CES,* July 1989).
10. Committee on Science, Engineering, and Public Policy, Panel on Policy Implications of Greenhouse Warming, National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base* (Washington, *DC:* National Academy Press, 1992).
11. Corell, R.W., Geosciences, National Science Foundation testimony at hearings before the House Subcommittee *on the* Environment, *Committee* on Science, Space, and Technology, May 5, 1992.
12. Corell, R.W., Committee on Earth and Environmental Sciences, Subcommittee on Global Change Research, and Geoscience, National Science Foundation, testimony before the House Subcommittee on Space, Committee on Science, Space, and Technology, Mar. 30, 1993.
13. Dowlatabadi, H., and M.G. Morgan, "A Model Framework for Integrated Studies of the Climate Problem," *Energy Policy,* March 1993, pp. 209-221.
14. Dowlatabadi, *H.,* and M.G. Morgan, "Integrated Assessment of climate Change," Science, vol. 259, Mar. 26, 1993, pp. 1813, 1932.
15. Dowlatabadi, H., and M.G. Morgan, Department of Engineering and Public Policy, Carnegie Mellon University, testimony at hearings before the House Committee on Science, Space, and Technology, May 19, 1993.
16. Earth Observation Satellite Company (EOSAT), *Landsat Technical Notes,* EOSAT, September 1992.
17. Edmonds, J.A., H.M. Pitcher, F.NJ. Rosenberg, and T.M.L. Wigley, "Design for an Integrated Global Environmental Change Model," report prepared for the Electric Power Research Institute and the U.S. Department of Energy, July 13, 1993 (draft).
18. Federal Geographic Data Committee, Wetlands Subcommittee, *Application of Satellite Data for Mapping and Mom"toting Wetlands,* fact-finding draft report, April 1992.
19. Gibbons, J.H., Assistant to the President for Science and Technology, memorandum to Frederick M. Bernthal, Acting Director, National Science Foundation July 8, 1993.
20. Gibbons, J.H., Assistant to the President for Science and Technology, testimony at hearings before the Senate Committee on Energy and Natural Resources, Mar. 30, 1993.
21, Gore, A., "From Red Tape to Results: Creating a Government that Works Better and Costs Less," report of the National Performance Review, Sept. 7, 1993.
22. Gramp, K.M., A.H. Teich, and S.D. Nelson, *Federal Funding for Environmental R&D: A Special Report,* R&D Budget and Policy Project, The American Association for the Advancement of Science, AAAS publication number 92-48S, 1992 (Washington, DC: AAAS).
23. Herrick, C.N., "Science and Climate Policy: A History Lesson," Issues *in Science and Technology,* vol. *8, No. 2,* Winter 1991-92, pp. 56-57.
24. Herrick, C.N., and D. Jamieson, "The Social Construction of Acid Rain: Some Implications for Science/Policy Assessment" paper to be presented at the 18th annual meeting of the Society for the Social Studies of Science, Nov. 19-21, 1993.
25, Interagency Task Force on Acid Precipitation *Annual Report 1982 to the President and Congress (Washington DC:* National Acid Precipitation Assessment Program, 1982).
26. Intergovernmental Panel on Climate Change (IPCC), World Meteorological Organization, and United Nations Environment Program, *Climate Change: The IPCC Impacts Assessment,* report prepared for IPCC by Working Group II, W. McG. Tegart, G. Sheldon, and D. Griffith (eds.) (Canberra, Australia: Australian Government Publishing Service, 1990).
27. Intergovernmental Panel on Climate Change (WCC), World Meteorological Organization, and United Nations Environment Program, *Climate Change: The IPCC Response Strategies,* report prepared for IPCC by Working Group III, 1990.
28. Intergovernmental Panel on Climate Change (IPCC), World Meteorological Organization, and United Nations Environment Program, *Climate Change: The IPCC Scientific Assessment,* report prepared for IPCC by Working Group I, J. Houghton, G. Jenkins, and J. Ephraums (eds.) (Cambridge, England: Cambridge University Press, 1990).

29. Intergovernmental Panel on Climate change, World Meteorological Organization, and United Nations Environment Program, *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment,* report prepared for IPCC by Working Group I, J. Houghton, B. Callander, and S. Varney (eds.) (Cambridge, England: Cambridge University Press, 1992).
30. Jamieson, D., 'Managing the Future: Public Policy, Scientific Uncertainty, and Global Warming, " in: *Upstream/ Downstream: Issues in Environmental Ethics,* D. Scherer (cd.) (Philadelphia, PA: Temple university Press, 1990).
31. Lancaster, J., "Global Warming Integrated Assessment and Interdisciplinary Research," proceedings of a Batelle workshop on Regional Impacts of Climate Change, Oct.. 18-21, 1993, Richland, WA (Richland, WA: Batelle Pacific Northwest Laboratory, in press).
32. Lubchenco, J., & al., "The Sustainable Biosphere Initiative: An Ecological Research Agenda," *Ecology,* vol. 72, No. 2, 1991, pp. 371-412.
33. Mahlman, J.D., "Understanding Climate Change," in: *Joint Climate Project to Address Decision Makers' Uncertainties: Report of Findings (Washington DC:* Science and Policy Associates, Inc., 1992).
34. National Commission on the Environment, *Choosing a Sustainable Future, report* of the National Commission on the Environment, convened by the World Wildlife Pond (Washington, DC: Island Press).
35. National Research Council, Global *Environmental* Change: *Understanding the Human Dimensions* (Washington, *DC: National Academy* Press, 1992).
36. National Research Council, Science *and the National Parks* (Washington, *DC:* National Academy Press, 1992).
37. National Research Council, *Research to Protect, Restore, and Manage the Environment (Washington DC:* National Academy Press, 1992).
38. National Research Council, *Science, Technology, and the Federal Government: National Goals for a New Em* (Washington, DC: *National* Academy Press, *1993).*
39. Oversight Review Board of the National Acid Precipitation Assessment Program (NAPAP), *The Experience and Legacy of NAPAP: Report to the Joint Chairs Council of the Interagency Task Force* on Acid *Deposition* (Washington, *DC:* NAPAP, *April* 1991).
40. parsons, T., "Usefulness of Climate Modela in Developing Climate Treaties," contractor report prepared for the Office of Technology Assessment, Sept. '20, 1993.
41. Roughgarden, J., S.W. Running, and P.A. Matson, "What Does Remote Sensing Do for Ecology? ''Ecology, vol. 726,1991, pp. 1918-22.
42. Rubin, E.S., L.B. Lave, and M.G. Morgan, 'Keeping Climate Research Relevant," *Issues in Science and Technology,* VOL 8, No. 2, Winter 1991-1992, pp. 47-5S.
43, Running, S.W., "Estimating Terrestrial primary Productivity by Combining Remote Sensing and Ecosystem Simulation," in: *Remote Sensing of Biosphere Functioning,* RJ. Hobbs and HA. Mooney (eds.) (New York, NY: Springer-Verlag New York, Inc., 1990), pp. 65-86.
44. Sayn-Wittgenstein, L., "Land cover Mapping for Mission to Planet Earth," *IEEE Technology and Society Magazine, Spring* 1992, pp. 16-22.
45, Science and Policy Associates, Inc., *Joint Climate Project to Address Decision Makers' Uncertainties: Report of Findings* (Washington, DC: Science and Policy Associates, Inc., 1992).
46. United Nations, *United Nations Convention on Climate Change, Article 2 and Article 4, Sec. 2(b),* 1992.
47. Us. congress, General Accounting Office (GAO), *Acid Rain: Delays and Management Changes in the Federal Research Program,* GAO/RCED-87-89 (Washington, *DC:* GAO, April 1987).
48. Us. congress, Office of Technology Assessment, *Federally Funded Research: Decisions for a Decade,* OTA-SET-490 (Washington DC: Us. Government Priming Office, May 1991).
49. Us. -, Office of Technology Assessment, The *Future of Remote Sensing from Space: Civilian Satellite Systems and Applications,* OTA-ISC-558 (Washington, *DC: Government Printing office,* July *1993).*
50. Us. congress, Office of Technology Assessment, "EOS and USGCRP: Are We Asking and Answering the Right Questions?" background paper prepared by OTA (in press).
51. U.S. Environmental Protection Agency, *The Potential Effects of Global Climate* Change on *the United States,* EPA-23@05-89-050, J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental protection Agency, December 1989).
52. Us. Environmental protection Agency, *Policy Options for Stabilizing Global Climate,* Report to Congress, EPA 21P-2003.1, D. Lashof and D. Tirpak (eds.) (Washington, DC: U.S. Environmental protection Agency, Office of Policy, Planning and Evaluation December 1990).
53. Ustin, S.L., et al., "opportunities for Using the EOS Imaging Spectrometers and Synthetic Aperture Radar m Ecological Models," *Ecology,* vol. 72, No. *6,* 1991, pp. 193445.
54. Wickland, D.E., "Mission to Planet Earth: The Biological Perspective," *Ecology,* vol. 72, No. *6,1991,* pp. 1923-33.
55. Wright, G.R., *Wildlife Research and Management in the National Parks (Chicago, IL:* University of Illinois Press, 1992).

Coasts 4

Status

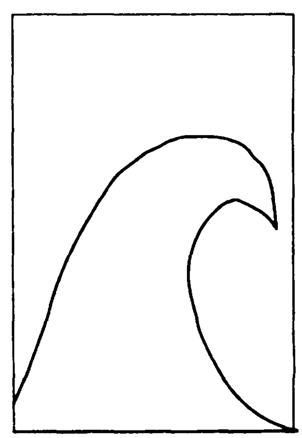
- Population is increasing in coastal areas faster than in any other region of the country.
- More people and property are becoming exposed to coastal hazards daily.
- The costs of mitigating and recovering from disasters is steadily increasing.

Climate Change Problem

- Sea level rise.
- Possibility of more frequent and/or more intense coastal storms.
- Temperature and precipitation impacts.

What Is Most Vulnerable?

- Low-relief, easily eroded shorelines (e.g., Southeast and Gulf coasts).
- Subsiding areas (e.g., Mississippi River Delta).
- Structures immediately adjacent to the ocean.



Impediments to Better Management

- Popularity of coastal areas.
- Insufficient incentives to take adequate precautions.
- Perceived or actual cost.
- Private property concerns.
- Institutional fragmentation.

Types of Responses

- Revamp the National Flood Insurance Program
- Improve disaster-assistance policies.
- Revise the Coastal Barrier Resources Act and the Coastal Zone Management Act.
- Change beach-nourishment guidelines.
- Alter the U.S. Tax Code.

OVERVIEW

The subject of this chapter—the coastal zone-is somewhat distinct from that of the other chapters in this report because it focuses on a readily identifiable geographic area and on the built components of this area rather than on a specific natural resource. The coastal zone can be broadly characterized both as a popular place to live, work, and play and as an area where some unique, climate-related risks to people, property, and ecosystems occur. Population near the coast is growing faster than in any other region of the country, and the construction of buildings and infrastructure to serve this growing population is proceeding rapidly. As a result, protection against and recovery from hazards peculiar to the coastal zone, such as hurricanes and sea level rise, are becoming ever more costly. The combination of popularity and risk in coastal areas has important near-term consequences for the safety of coastal residents, protection of property, maintenance of local economies, and preservation of remaining natural areas.

Longer-term climate change impacts are likely to exacerbate existing problems associated with living in the coastal zone. Sea level rise is a potential climate change impact unique to coastal areas and one that could lead to increased flooding and erosion in areas already vulnerable to the dynamic forces of wind, waves, currents, and tides. Climate change could also lead to more frequent and/or severe hurricanes and other coastal storms. Scientists are less confident about this possibility than they are about sea level rise, but even if coastal storms are unaffected by climate change, their impact on the coast will increase as the sea rises.

Climate change in coastal areas would clearly be costly for Federal, State, and local governments. These costs are associated both with the inherent risks of living in the coastal zone and with how these risks are allocated among various public and private entities. The present system of risk allocation in the coastal zone does not promote an adequate appreciation of the current and potential hazards associated with living in this area. As a result, certain types of risky development are encouraged (or at least not discouraged) that could lead to greatly increased Federal outlays in the future. One need only look at the costs to the Federal Government for disaster assistance after Hurricanes Hugo (about $1.6 billion), Andrew (about $2.1 billion), and Iniki (about $400 million) to appreciate the potential magnitude of the outlays involved. Moreover, in each of these cases, total costs were considerably greater. Climate change will likely add to the risks and costs of living in the coastal zone, so it is essential that these risks be well-understood by all stakeholders and that coastal development and preservation are guided by this understanding. The sooner policies that encourage an adequate appreciation of risk are in place, the easier and less costly adaptation to a changing climate is likely to be.

Risk management is a Federal, as well as a State and local, responsibility. The Federal Government has an interest in promoting sound planning and public safety in an effective and efficient manner. Federal coastal zone policies can be improved in several ways to better guide the decisions of those living in coastal areas. Considered in this chapter are policies to improve the National Flood Insurance Program, disaster assistance, beach nourishment and shoreline protection, coastal zone and barrier-island management, and the U.S. Tax Code. In other chapters, we consider related water, wetlands, and preserves issues (ch. 5 and vol. 2, chs. 4 and 5).

VULNERABILITY OF COASTAL AREAS

Climate-related risks, from blizzards to tornadoes, are inherent to many parts of the United States. However, the coastal zone--that narrow boundary zone where ocean and dry land meet and most directly influence one another-is a dynamic area of larger-than-average risk. Hurricanes and other violent coastal storms cause hundreds of millions of dollars in damage every year and are responsible for numerous deaths. For example, the two most destructive natural disasters of 1992, Hurricanes Andrew and Iniki did considerable damage in the coastal zone, and these two catastrophes accounted for almost 80 percent of the more than $21 billion of insurance-industry claims for the 10 most costly catastrophes in 1992.

Less dramatic than the destruction of homes and other structures by storms-but ultimately very costly-is coastal erosion. A significant proportion of the U.S. coastline is eroding. Although rates of erosion are highest during major storms, long-term erosion caused by the unremitting action of normal waves, wind, and tides adds much to the risks and costs of living in coastal areas. Structures in or near eroding areas are increasingly at risk as erosion progresses. Furthermore, erosion can be exacerbated by human activities, including the deepening of ports and harbors, maintenance of tidal inlets, damming of major rivers, and pumping of coastal groundwater and petroleum.

The remaining undeveloped parts of the coastal zone (e.g., wetlands and many barrier islands) are also at risk. They are vulnerable both to the effects of climate change and to human encroachment and thus may need special attention if society wishes to preserve them.

The coastal zone may be the region of the country most vulnerable to climate change. Like other areas, it would be affected by higher temperatures and changes in precipitation In addition, coastal regions would have to contend with the changing sea level and could be subject to more-frequent and/or more-intense hurricanes and other coastal storms. Such expressions of climate change would cause, among other things, increased coastal flooding and erosion, higher storm surges, increased wind damage, and increased saltwater intrusion into freshwater aquifers.

Demographic Trends

Increases in population and development in coastal areas have been dramatic in recent decades. Between 1%0 and 1990, the population of coastal counties grew from 80 million to roughly 112 million people. People living in coastal counties in 1990, about 44 percent of the total U.S. population, occupied an area that comprises just 11 percent of the United States outside Alaska.[1] Population density in coastal counties, roughly 350 people per square mile (135 people per square kilometer),[2] is more than four times the national average. Projections suggest that by the year 2010, coastal populations will grow to 127 million (15). Seventeen of the 20 States expected to grow by the greatest amount by 2010 are coastal. Florida alone is expected to add 11 million people to its population, a 230 percent change from 1960 (15).

With population growth has come development and a corresponding increase in the exposure of property to natural disasters. For example, the property-casualty insurance industry has estimated that its insured property exposure in residential and commercial coastal counties in the 18 Gulf and Atlantic Coast States increased from $1.13 to $1.86 trillion between 1980 and 1988 (l). This change is a result of increasing property values as well as of greater numbers of properties insured.[3] Insurance-industry liabilities in some States have grown much faster during this period than the coastal-State average-by 83 percent in South Carolina, a victim of Hurricane Hugo in 1989, for example (l). Many insurance compa-

[1] The coastal zone baa been defined *in* a variety of ways-for example, as the area encompassed by counties adjacent to the ocean, the area below a specified elevation, or the area within an arbitrary number of miles from the coast. About 53 percent of the U.S. *population lives in counties* entirely or substantially within 50 miles (80 kilometers) of the coast (89).

[2] To convert square miles to square kilometers, multiply by 2.590.

[3] These figures do not include amounts for the Pacific Coast, near-coastal cities, such as Houston and Philadelphia that could be (and have been) affected by coastal storms, or any uninsured property or self-insured government property.

NOAA

The concentration of people in coastal areas is steadily increasing. Densely populated Miami Beach, shown here, was spared the major losses suffered only a few miles to the south when Hurricane Andrew struck in 1992. The city may not always be so fortunate.

nies decided to pull out of Florida after Hurricane Andrew, and others are increasing premium rates significantly, perhaps an indication of future trends.

Sea Level Rise

Continuing sea level rise and associated long-term shoreline erosion could be a substantial problem for some U.S. coastal regions (see, for example, fig 4-l). Global sea level has risen by some 4 to 8 inches (10 to 20 centimeters)[4] in the past 100 years, largely as a result of melting of land-based ice sheets and glaciers (64).[5] Along the U.S. Gulf Coast, *relative sea level rise*[6] has been closer to 12 inches (67). According to the Intergovernmental Panel on Climate Change (WCC), sea level could rise another 10 inches or so in the next 50 years. Estimates of future sea level rise due to global warming vary greatly, but the change is likely to be between 12 and 43 inches by the year 2100, with a "best estimate" of 26 inches above levels that would otherwise exist (40). Future sea level rise in this range could expand areas where coastal flooding and inundation occur, and coastal erosion could increase. A 20-inch rise could inundate more than 5,000 square miles (mi^2, or about 13,000 square kilometers)[7] of dry land and an additional 4,000 mi^2 of wetlands in the United States if no actions are taken to protect threatened areas (63, 82). The Federal Emergency Management Agency (FEMA) suggests that the number of households subject to flooding would increase from about 2.7 million now to almost 6 million by 2100 as a result of a combination of a 12-inch sea level rise and coastal area population growth (21).

Sea level rise would especially be a problem along the low-lying barrier-island system of the Atlantic Coast from New York south to Florida and along the Gulf of Mexico Coast, where small, vertical rises in sea level would cause large, horizontal movements in the shoreline and where the full effects of storm surges, winds, waves, and tides are felt (fig. 4-2). High-risk shorelines are characterized by low-relief, easily eroded surfaces, retreating shorelines, evidence of subsidence, and high wave and tide energies. A coastal vulnerability index based on these factors has been used to identify areas most vulnerable to future sea level rise (35).

The most vulnerable shorelines in the conterminous United States are in the Gulf of Mexico, and include virtually all of the Louisiana shoreline and parts of the Texas coast. These areas have anomalously high relative sea level rise, and erosion there is coupled with low elevation and mobile sediments. Forty percent of the entire Gulf Coast is retreating at rates greater than 80 inches

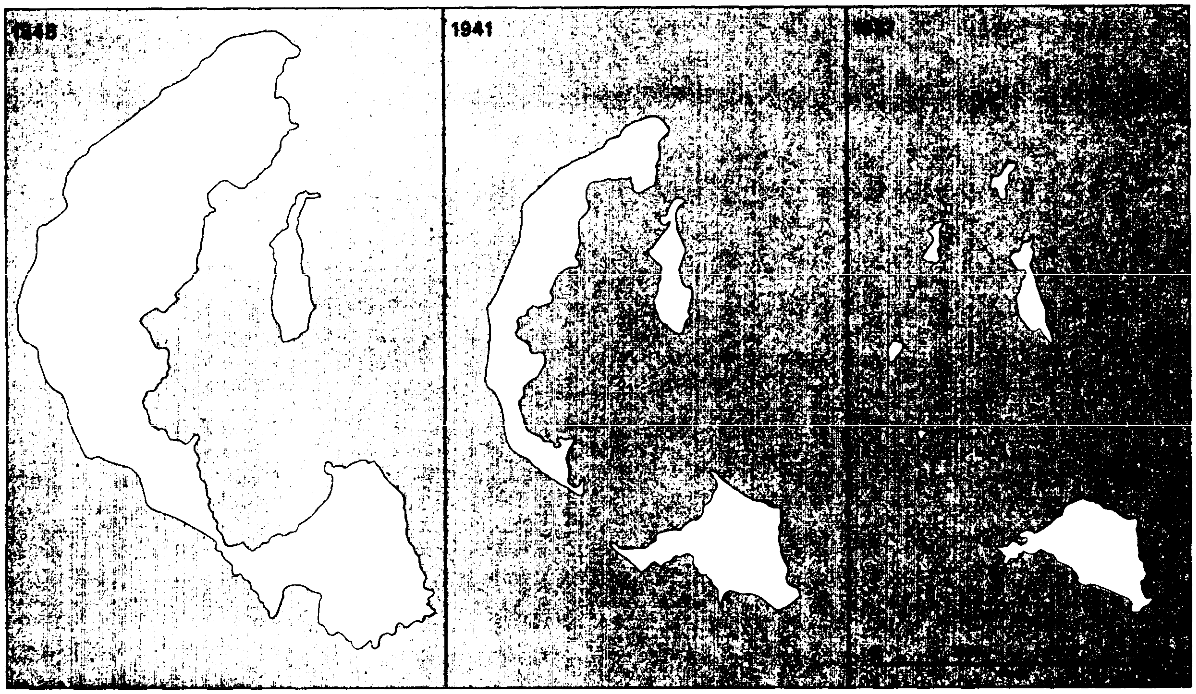
4 To convert inches to centimeters, multiply by 2.54,

5 Other factors include thermal expansion of the oceans, the slow rebound of land after melting of glaciers (glacial isostatic adjustment), and local tectonic activity.

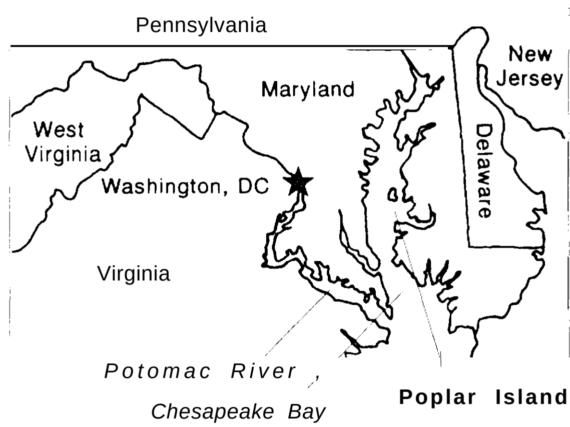
6 As the sea rises, adjacent land may be independently increasing or decreasing in elevation due to tectonic activity, compacting of sediments, or subsurface pumping of petroleum or water, for example. Relative sea level rise reflects the net effect of all these factors.

7 To convert square miles to square kilometers, multiply by 2.590.

Figure 4-1—Historical Land Loss of Poplar Island in Chesapeake Bay as a Result of Sea Level Rise and Erosion



per year. The highest rate of relative sea level rise in the United States occurs in Louisiana, where the average rate during the past 50 years has been more than 0.3 inches per year (35). About half of all land estimated to be inundated from sea level rise is in Louisiana. The Mississippi River Delta is especially at risk. In the absence of adequate protective measures, coastal cities such as Galveston, Texas, would frequently suffer intolerable flooding (16, 81, 83).

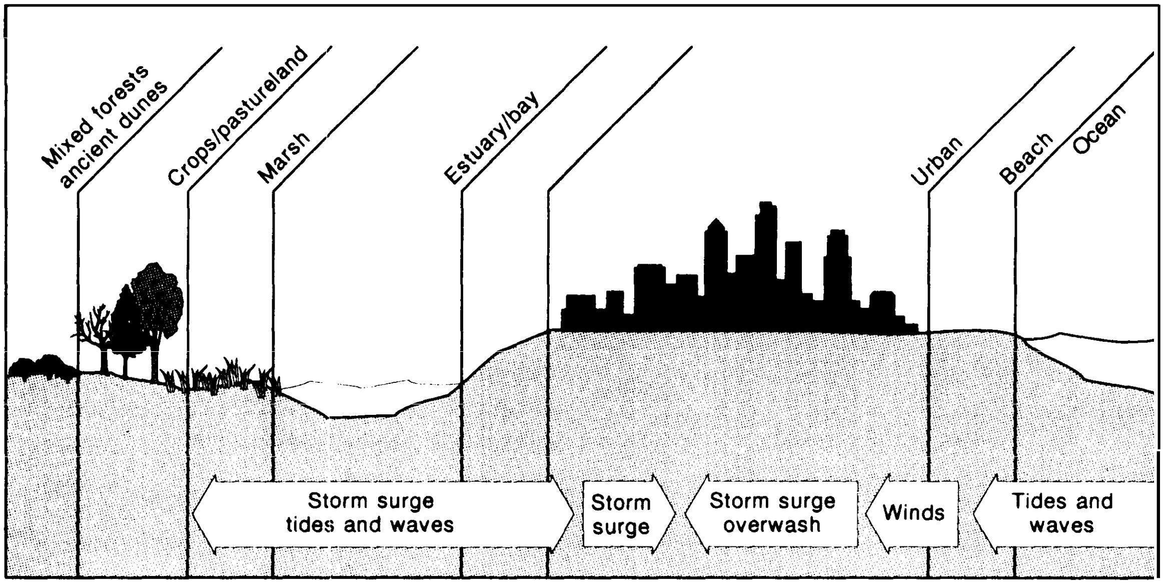


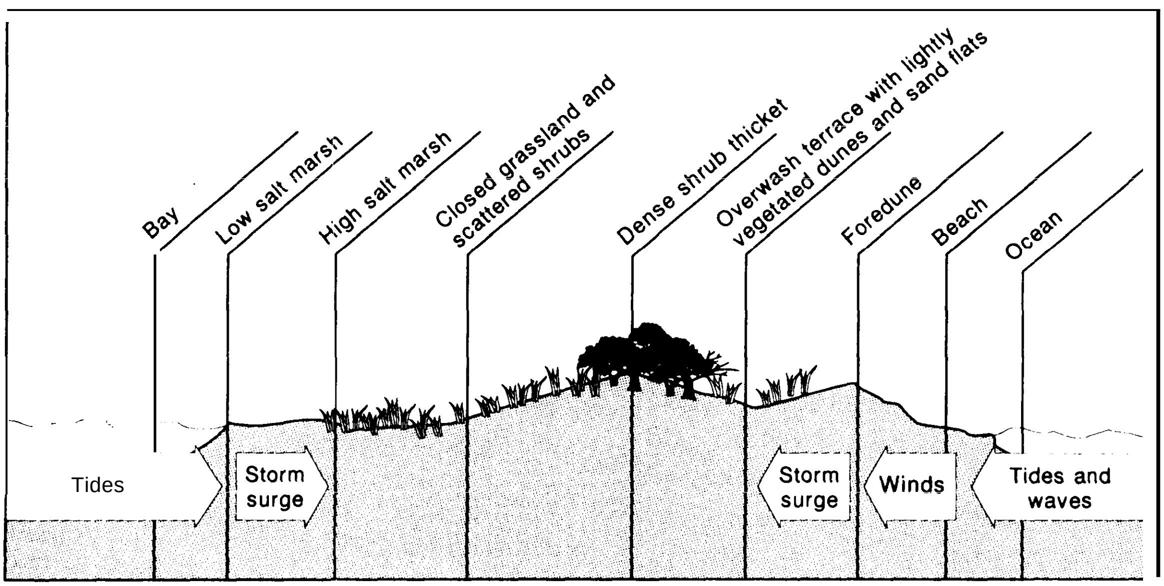
SOURCE: S. Weatherman, University of Maryland, College Park

The highest-risk shorelines along the Atlantic Coast include the outer coast of the Delmarva Peninsula, northern Cape Hatteras, Long Island, and segments of New Jersey, Georgia, and South Carolina. Heavy damage from periodic flooding and some loss of land due to inundation can be expected in such coastal cities as Atlantic City, New Jersey; Ocean City, Maryland; Charleston, South Carolina; and Miami Beach, Florida, if the sea level rises as predicted and no steps are taken to protect against it (48). About 25 percent of the Atlantic Coast is eroding; 8 percent is accreting.

Most of the tectonically active West Coast of the United States is steeper than the Atlantic and Gulf Coasts. Thus, western coastal areas are generally less Vulnerable to sea level rise. How-

Figure 4-2-Schematics of a Developed and an Undeveloped Barrier Island





NOTE: General locations of land-use and land-cover types are shown In relation to dominant shoreline process.

SOURCE: R. Dolan, University of Virginla, Charlottesville.

ever, areas such as the low-lying San Joaquin-Sacramento Delta (adjacent to San Francisco Bay—see box 5-A), the barrier beaches of Washington and Oregon, and parts of the Puget Sound lowlands are all quite vulnerable to sea level rise (35). The Pacific Coast generally is less vulnerable to erosion, too, because erosion-resistant rocks prevail over unconsolidated sediments. Only about 6 percent is eroding.

Several studies have attempted to estimate the possible costs of protecting U.S. coastlines from a rising sea. On the basis of results of studies commissioned by the Environmental Protection Agency, the cumulative costs of coastal defensive measures in populated areas have been estimated to be from $100 to $350 billion for a 40-inch rise in sea level by 2100 (83).[8] More recently, the U.S. Army Corps of Engineers has used similar data to make the same calculation but with different assumptions (e.g., about the protection measures that would most likely be used). The Corps estimates maximum costs at less than $120 billion (in 1992 dollars) (86).

The large spread between the estimates suggests that attaching great significance to any dollar figure for protecting the coast against sea level rise should be done cautiously. Of necessity, all such studies are based on a large number of assumptions about an uncertain future—especially the degree to which sea level is likely to rise in the next 100 years-and on extrapolations from a few well-studied areas to all vulnerable coastlines. Defensive and mitigative strategies, however, are site-specific and cannot easily be generalized nationwide (60). Also, the current IPCC "best estimate" for sea level rise by 2100 is 26 inches, which, if realized, could mean that protection costs would be much lower than those reported above. Furthermore, the above cost estimates, accumulated over more than 100 years, have not been discounted to present worth. Using the Corps' high estimate of $120 billion and a discount rate of 3 percent, the present worth of investment during this period would be $25 billion, or, equivalently, an average annual cost of $700 million. The costs of protecting against a rising sea may be manageable, but they will not be trivial.

Substantial damage to the natural environment could also result from sea level rise, including inundation of large areas of coastal wetlands (63, 81) and loss of biodiversity (73) (see vol. 2, chs. 4 and 5). The value of lost land (wetlands and undeveloped dry land) as a result of sea level rise has been estimated to be from $50 to $250 billion by 2100 (83). Losses of wetlands will be largest where human development, such as construction of bulkheads and houses, impedes the natural landward migration of wetlands in response to sea level rise (82). (For more on wetlands, see vol. 2, ch. 4.) Also, some human activities outside the coastal zone, such as construction of upland dams (which trap sediments that would otherwise replenish beaches), can thwart natural processes that could otherwise mitigate the potential erosion and flooding caused by an accelerated sea level rise (40).

Hurricanes and Coastal Storms

Hurricanes and severe coastal storms are among the most destructive and costly of natural phenomena. Flooding, erosion, and wind damage caused by such storms result in many lost lives and hundreds of millions of dollars of property damage every year.

The East and Gulf Coasts of the United States are especially vulnerable to hurricanes. Since 1871, roughly 250 hurricanes of varying intensity have struck parts of the coast between Texas and Maine. Virtually no segment of this coast has been spared (fig. 4-3A) (28). The destructive potential of a hurricane is a function of both its intensity (see box 4-A) and the density of development in the area affected. As develop-

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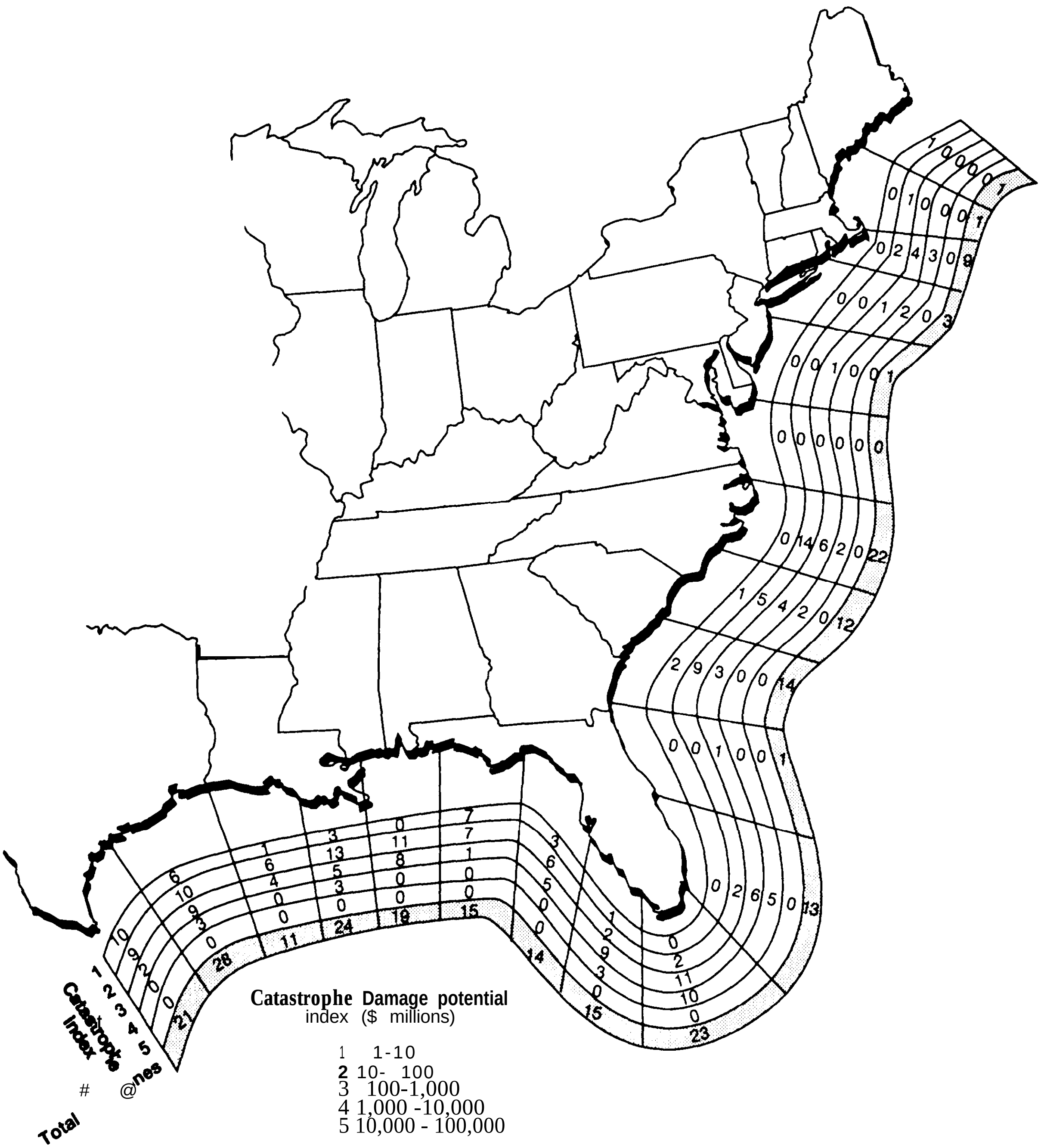
8 The authors of reference 83 consider their estimates conservative because they do not take into account impacts not readily quantified or the costs of protecting future development.

Figure 4-3A--Intensity of Historic Hurricanes

NOTE: Estimate of the Saffir-Simpson intensity at landfall of tho 247coastal crossings by hurricanes that affected the Gulf or East Coast in the ll9-year period between 1871 and 1990. Total hurricanes striking each segment of coast plus the number of hurricanes of each intensity are shown. For example, 23 hurricanes struck the southern tip of Florida during this period. Only one was a category 5 hurricane at landfall. Figure 4-3B shows that the present-day damage-producing potential of each of these 23 hurricanes was greater than $lO million but less than $lO billion (i.e., fell into categories 2, 3, or 4).

Figure 4-3B--Damage-Producing Potential of Historic Hurricanes



NOTE: Estimate of the catastrophe index, which shows the present-daydamage-producing potential of the 247 land-falling hurricanes that occurred somatime in the past 119 years. Numbers of hurricanes In each damage category are shown. For example, 10 hurricanesthat have struck the southern tip of Florida were strong enough to cause between $1 and $10 billion in damages if they occurred today (category A). Hurricane Andr- is not Included in the data, but It would be the first to fall into category 5.

SOURCE: D. Friedman, Natural Hazards Research Program, Travelers Insurance Co., "estimation of Damage-Producing Potentials of Future Natural Disasters in the United States Caused by Earthquakes and Storm%" paper presented at the International Conference on the Impact of Natural Disasters, Los Angeles, CA, 1991.

Box 4-A-Saffir-Simpson Hurricane-Intensity Scale

Category O

1. Winds less than 74 mph (119 km/h).[1]
2. Storm surge less than 4.0 feet (1.2 meters).[2]

Abroad coastal area may experience some damage to shrubbery, signs, and small structures and possibly some beach erosion, but the overall scope and impact of damage would not likely require relief action by the Federal Government.

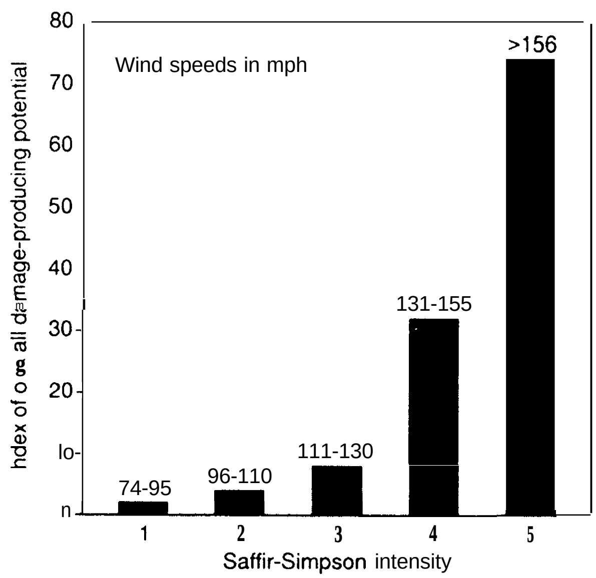
Category 1

1. Winds 74 to 95 mph; some damage to shrubbery, trees, and foliage; no real damage to building structures; some damage to poorly constructed signs, etc.
2. Storm surge 4 to 5 feet above normal; low-lying coastal roads inundated; minor pier damage; some small craft in exposed anchorages break moorings.

Category 2

1. Winds 96 to 110 mph; considerable damage to shrubbery and tree foliage; some trees blown down; no major damage to building structures.
2. Storm surge 6 to 8 feet above normal; coastal roads and low-lying escape routes inland cut by rising water 2 to 4 hours before arrival of the hurricane's center; considerable pier damage; marinas flooded; small craft in unprotected anchorages break moorings; evacuation of some shoreline residences and low-lying island areas required.

Safflr-Simpson Hurricane-intensity Scale



NOTE: To convert miles per hour to kilometers par hour, multiply by 1 .s09.

SOURCE: Adapted from P. Hebert, J. Jarrell, and M. Mayfield, *The Deadliest, Costliest, and Most Intense United States Hurricanes of This Century (and Other Frequently Requested Hurricane Facts)* (Coral Gables, FL: National Hurricane Center, 19S2).

Category 3

1. Winds 111 to 130 mph; damage to shrubbery and trees; foliage off trees; large trees blown down; some structural damage to small residences and utility buildings.
2. Storm surge 9 to 12 feet above normal; serious flooding at coast, with many smaller structures near coast destroyed; larger structures damaged by battering offloading debris; low-lying escape routes inland cut3 to 5 hours before center arrives; terrain continuously lower than 5 feet maybe flooded inland 8 miles or more; evacuation of low-lying residences within several blocks of the shoreline may be required,

Category 4

1. Winds 131 to 155 mph; shrubs and trees down; all signs down; extensive roofing-material damage; extensive window and door damage; complete failure of roof structures on many small residences.

[1] To convert miles per hour to kilometers per hour, multiply by 1.609. Speeds given here are at standard anemometer elevations. An anemometer is a device for measuring windspeed.

[2] To convert feet to meters, multiply by 0.305.

2. Storm surge 13 to 18 feet above normal; terrain continuously lower than 10 feet may be flooded inland as far as 6 miles; major darnage to lower floors of structures near the shore due to flooding and battering action; low-lying escape routes inland cut 3 to 5 hours before center arrives; major erosion of beach areas; massive evacuation of all residences within 1,500 feet of the shoreline and of single-story residences on low ground within 2 miles of the shoreline maybe required.

category 5

1. Winds greater than 155 mph; shrubs and trees down; roofing damage considerable; all signs down; severe and extensive window and door damage; complete failure of roof structures on many residences and industrial buildings; extensive glass failure; small buildings overturned and blown away.

2. Storm surge heights greater than 18 feet above normal; major damage to lower floors of all structures located less than 15 feet above sea level and within 1,500 feet of the shoreline; low-lying escape routes inland cut 3 to 5 hours before center arrives; massive evacuation of residential areas situated on low ground within 5 to 10 miles of the shoreline may be required.

SOURCE: P. Hebert, J. Jarell, and M. Mayfield, *The Deadliest, Costliest, and Most Intense United States Hurricanes of This Century (and Other Frequently Requested Hurricane Facts)* (Coral Gables, FL: National Hurricane Center, 19S2).

ment has expanded, exposure to coastal risks has increased dramatically. Table 4-1 compares damages from 49 hurricanes between 1949 and 1986 with damages those same hurricanes would have caused if they had occurred in 1987. Figure 4-3B shows the current damage-producing potential of the 247 hurricanes that struck the United States between 1871 and 1990. The different values, after adjusting for inflation, are due to increases in the size of the market (i.e., the amount of development) and the percentage of the market insured (27). For example, Hurricane Betsy, a category 3 storm, caused about $3.1 billion of insured losses in 1965 (adjusted to 1987 dollars). Had it struck in 1987, the insured losses would have been $6.3 billion.

Applied Insurance Research, Inc., in Boston, has developed estimates of total losses for major U.S. cities of a major hurricane strike. They estimate, for example, that a category 5 hurricane could generate $43 billion (in 1993 dollars) in losses in Galveston, Texas; $52 billion in Fort Lauderdale, Florida; and $34 billion in Hampton, Virginia (see table 4-2).

Hurricane Andrew was a category 4 hurricane when it struck South Florida in August 1992. The third most intense storm to strike the United States this century,[9] Andrew's total damages were more than 4 times greater than total damages from Hurricane Hugo, the former damage record holder. Andrew's estimated cost to property insurers as of February 1993 was at least $15.5 billion (72). However, this figure does not include losses involving uninsured property, such as damage to Government military facilities or other public property; utility equipment, such as power lines; economic losses, such as crop damage and lost tax revenue; and aircraft. It also does not include the cost of emergency services or property insured under the National Flood Insurance or Small Business Administration programs (72). The **total** losses from Andrew are likely to be greater than $30 billion. Moreover, if Andrew had struck 15 miles further north, in central Miami, damages could have been twice as much.

9 The two storms that hit land in the United States this century that were of greater intensity were Hurricane Camille, which struck the Mississippi coast in 1%9, killing 256 people, and the Labor Day hurricane that struck the Florida Keys in 1935, killing at least 600 (3). Hugo ranks 11th in intensity.

Table 4-l—Estimates of Insurance-Industry Potential Losses in 1987 Resulting from a Recurrence of Past Hurricanes

Year	Hurricane	Scenario 1 Damages in year-of-occurrence dollars ($ millions)	Scenario 2 Damages expressed in 1987 dollars ($ millions)	Scenario 3 Damages adjusted for inflation, market size, and insured share in 1987 dollars ($ millions)
1986	Charley	7	7	7
1986	Bonnie	21	22	22
1985	Kate	78	81	84
1985	Juan	44	46	47
1985	Gloria	419	436	440
1985	Elena	543	564	582
1985	Danny	37	39	40
1985	Bob	13	14	14
1984	Diana	36	40	41
1983	Alicia	675	790	893
1982	Iwa	137	170	192
1980	Allen	58	82	106
1979	Frederic	753	1,151	1,243
1979	David	122	187	217
1977	Babe	2	4	4
1976	Belle	23	45	53
1975	Eloise	119	259	352
1974	Carmen	12	28	36
1973	Delia[a]	3	8	11
1972	Agnes,[b]	8	22	36
1971	Ginger	2	6	8
1971	Edith	5	14	20
1971	Fern[a]	1	4	6
1971	Doria[a]	14	40	57
1970	Celia	310	1,007	1,602
1969	Camille	165	554	822
1986	Gladys	3	10	23
1967	Beulah	34	136	260
1966	Alma	5	22	59
1965	Betsy	715	3,096	6,300
1964	Isbell	2	9	*23*
1964	Hilda	23	104	204
1964	Dora	12	54	*137*
1964	Cleo	67	303	*815*
1961	Esther	4	20	*54*
1961	Carla	100	473	*1,263*
1960	Donna	91	430	*1,313*

a Tropical storm (maximum winds less than hurricane force).
b Wind damage only.

Note: Based on assumptions about changes in the cost of repair, size, and insured share of the affected property market since 1960.

Scenario l—Occurrence *of past hurrianes under original conditions.*

Scenario *2—Recurrence of past hurricanes with original market conditions, but using current value and cost-of-repair factor (inflation-adjusted only).*

Scenario *3--Recurrence of past hurricanes and their effect on current industry-insured properties, values, and costs of repair (combined market size, insured share, and inflation adjustment).*

SOURCE: D. Friedman, *Estimation of the Loss of Producing Potential of the Wind and Hail Perils to Insured Properties in the United States* (London, England: Insurance and Reinsurance Research Group, Ltd., 1987).

NOAA

Hurricane Andrew seen from space as it reached southeastern Florida on August 4, 1992. Andrew was one of the most destructive hurricanes in U.S. history. Estimated total losses of $30 billion would have been even higher had the eye of the hurricane struck heavily populated Miami a few miles to the north.

Neither Andrew nor Hugo hit major population centers.

On average, between 16 and 17 hurricanes per decade have occurred in the United States since 1900. About seven of these per decade have been major (37).[10] Much of the urban growth along the East and Gulf Coasts has occurred since 1%0, during which period hurricane and coastal-storm activity has been somewhat less than average (14 per decade between 1960 and 1990, of which about 5 per decade were major) (37). About 80 percent of people now living in hurricane-prone areas have never experienced a direct hit by a major storm (34). Prophetically, the National Committee on Property Insurance suggested in 1988 that the people of South Florida, who had not experienced a major hurricane since 1950, were living on borrowed time (58). Also, much coastal development since 1960 has been in the most vulnerable locations, including barrier islands,[11] beachfront areas, on or near coastal wetlands and estuarine shorelines, and in flood-hazard zones. Notably, many of the counties most susceptible to hurricanes (e.g., Monroe County, Florida, where the annual probability of a hurricane striking is 19 percent) are expected to grow at much faster rates than the Nation as a whole between now and 2000 (l).

Table 4-2—Estimated Cost of a Major Hurricane Striking Densely Populated Areas (or Major Cities)

Saffir-Simpson category[a]	Landfall location	Estimated total loss ($ billions)[b]
5	Galveston, TX	43
5	New Orleans, LA	26
5	Miaml, FL	53
5	Ft. Lauderdale, FL	52
5	Hampton, VA	34
4	Ocean City, MD	20
4	Asbury Park, NJ	52
4	New York City, NY	45
4	Long Island, NY	41

[a] Severity of the hurricane (5 is more severe than 4)
[b] 1993 dollars

SOURCE Applied Insurance Research, Inc , Boston, MA

Loss of life from hurricanes has declined over time, in large part due to improved weather forecasting and evacuation planning (34). For example, 35 deaths were caused by Andrew, whereas many hurricanes this century have caused many more than 100 deaths.[12] Although existing warning and prediction systems are likely to continue to improve, people continue to crowd into coastal areas, so the time required to evacuate them could increase. Aging infrastructure in some areas (see ch. 5) may also contribute to evacuation problems. Therefore, even without increased numbers or intensities of hurricanes (but more so with them), the potential exists for increased loss of life in the future.

10 Major storms are those classified as category 3 or greater.

11 Between 1955 and 1975, developed land on barrier islands increased by 153 percent (51).

12 & unnamed hurricane that struck Galveston, Texas, in 1900 caused more than 6,000 deaths.

Table 4-3--insured Losses Likely To Be Experienced Under Different Maximum-Wind-Speed Scenarios

storm	Class	Year	Estimated 1990 insured losses ($ billions)	Estimated 1980 insured losses if maximum wind speed increases ($ billion)		
				5 percent	10 percent	15 percent
Hugo	4	1969	4	5	7	9
Alicia	3	1963	2	3	4	6
Camille	5	1969	3	4	5	7

SOURCE: K. Clark, "Predicting Global Warming's Impact," Contingencies (newsletter of Applied Insurance Research, Inc., Boston, MA), May/June 1992.

Will the intensity or frequency of hurricanes and/or other storms increase in a warmer climate? General Circulation Models (GCMs) cannot simulate the occurrence of hurricanes in detail (40), but researchers have found that by modeling the doubling of carbon dioxide (CO_2, the number of simulated tropical disturbances-although not their intensity-increased (36) (see ch. 2 for a discussion of GCMS). There has also been some research on the relationship between rising sea-surface temperatures and hurricane severity and some suggestion that these may be positively correlated. However, no unambiguous correlation has yet been established. Some have suggested, for example, that hurricanes may be less intense in a warmer climate (13). Additional research is clearly needed to establish the relationship between global warming and hurricane intensity and frequency.

What is somewhat clearer is the nonlinear relationship between the maximum wind speeds of hurricanes and their damage-causing potential. Table 4-3 shows some examples of how insured losses would increase with maximum wind speed. If wind speeds for the three hurricanes shown had been 15 percent higher, insured wind losses would have more than doubled (13). Hence, if climate change leads to only marginally more-intense hurricanes, substantially greater damage can be expected.

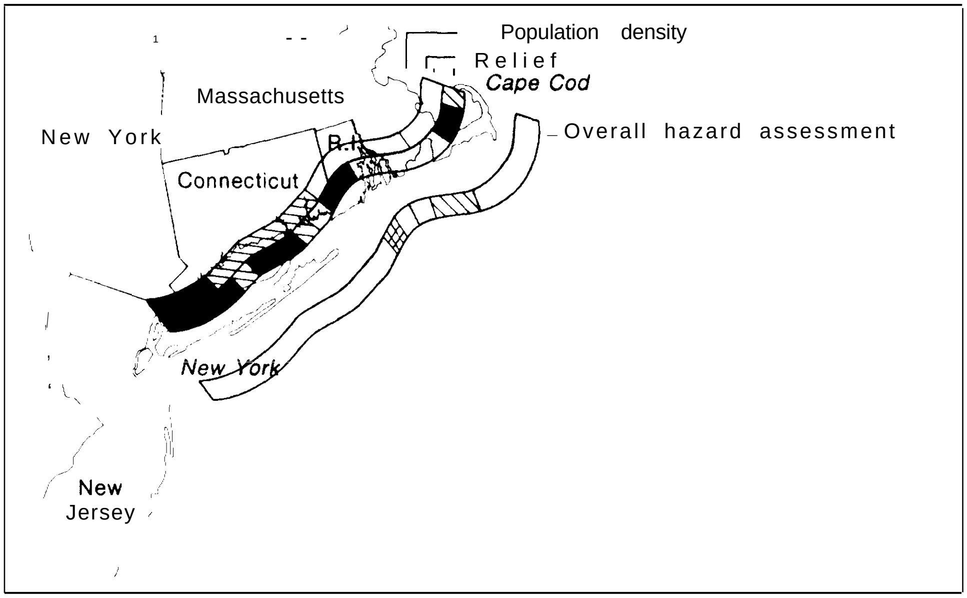
An Overall Coastal-Hazard Assessment

The U.S. Geological Survey (USGS) has combined information about a variety of natural processes and coastal characteristics with information about population density to develop an overall coastal-hazard map (90). Factors separately considered are coastal relief, shoreline change (a measure of sea level rise), storm surge, frequency of major storms, frequency of earthquakes and other earth movements, stabilization (a function of the density of structures), ice (important only in Alaska and the Great Lakes), and permafrost (perennially frozen ground, important in northern Alaska). Segments of the coast are rated from very high to very low risk in six categories. Figure 4-4 shows two simplified segments of the USGS map. The complete map, however, shows that Louisiana eastern Texas, parts of the Pacific Northwest, and much of Alaska and Hawaii are the most vulnerable segments of the U.S. coastal zone. USGS is currently in the process of producing more-detailed regional maps, which should be very helpful in assessing the vulnerability of U.S. coastal areas to climate change.

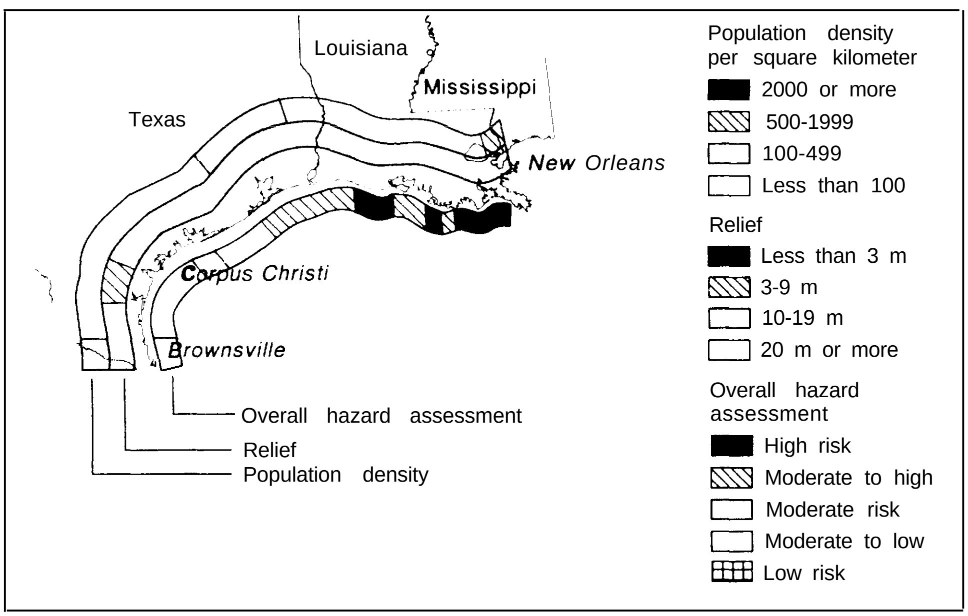
THE CHALLENGE FOR POLICY

Although development pressures in coastal areas are driven by many social and economic trends, government policies can influence the appropriateness, rate, quality, and location of development. Historically, government has subsidized coastal development, both directly and indirectly. In particular, four important programs and policies address the riskiness of living in the coastal zone: 1) the National Flood Insurance

Figure 4+-Coastal Hazard Assessment



New York to Massachusetts.



Texas to Louisiana.

SOURCE: U.S. Geological Survey (USGS), "Coastal Hazards," *National Atlas* of the *United States* of America(Reston, VA: USGS, 1985).

Program (NFIP), 2) Federal disaster assistance, 3) Federal beach-renourishment and shoreline-protection programs, and 4) the U.S. Tax Code. These programs and policies have clear benefits, but some of their elements have contributed to a distortion of the Nation's perception of the vulnerability of living in coastal areas and have lead to some inappropriate or ill-suited development. The goals of some coastal programs and policies are also often at cross-purposes with one another: improving coordination is as relevant in coastal areas as it is in other sectors discussed in this assessment.

National Flood Insurance Program

Congress made Federal flood insurance available in 1%8 through the creation of the National Flood Insurance Program (authorized under the National Flood Insurance Act, P.L. 90448). The NFIP was enacted to limit increasing flood-control and disaster-relief expenditures and to provide a pre-funded mechanism to more fully indemnify victims of flood-related disasters. It was also intended to limit unwise development in floodplains while at the same time providing affordable Federal insurance for structures located in special flood-hazard areas (14). Between 1978 and 1992, 430,000 flood-insurance claims were made, and total payments, including claims arising from Hurricanes Hugo, Andrew, and Iniki, have been nearly $4.0 billion (22).

The NFIP has been only partially successful. It has reduced somewhat the need for taxpayer-funded disaster assistance and has been a factor motivating local government mitigation efforts. Homes built in compliance with NFIP regulations are some 70 percent less likely to be damaged than those built before NFIP requirements went into effect. Before the program was created, affordable private flood insurance was generally not available. However, the program has also contributed to coastal development and has been criticized frequently for not adequately fostering prudent land use in hazardous areas.

The program is administered by the Federal Insurance Administration (FIA), a unit of FEMA. Under the NFIP, Federal flood insurance coverage is made available to owners of flood-prone property in communities that adopt and enforce a floodplain-management ordinance that meets the minimum program standards. Coverage is available both for the structure itself (up to $185,000 for a single-family structure) and for its contents (up to $60,000) (26). Participating communities must adopt certain minimum floodplain-management standards, including: 1) a requirement that new and substantially improved structures in the 100-year flood zone[13] be elevated to or above the 100-year flood level (generally known as *base flood elevation, or* BFE), 2) restrictions on new development in designated floodways (e.g., development within a floodway is prohibited if it results in raising the flood levels), and 3) a requirement that subdivisions be designed to minimize exposure to flood hazards. Additional standards are imposed within high-hazard coastal zones ("velocity" zones, or "V" zones), including requirements that buildings be elevated on pilings, all new development be landward of the mean high water value, the BFE include wave heights greater than 3 feet (0.9 meters),[14] ad new development on dunes not increase potential flood damage.

NFIP participation by a community is voluntary, but there are now strong incentives to participate. Because of limited participation initially, the 1973 Flood Disaster Protection Act (P.L. 93-234) required flood insurance for all federally backed mortgages (e.g., for Department of Veteran Affairs (VA) and Federal Housing Administration (FHA) loans) and for all loans obtained through federally insured and regulated

13'fbo area that would be inundated by a flood whose elevation has a 1 percent chance of being equaled or exceeded in any year, that is, that would occur on average only once every 100 years.

14 To convert feet to meters, multiply by 0.305.

financial institutions. Also, disaster-assistance grants to local governments for repair of public facilities are reduced for those governments not participating in the program (although individual property owners need not have flood insurance to be eligible for individual and family disaster-assistance grants). As a result, communit y participation has been high, and about 82 percent of the 22,000 flood-prone communities have adopted minimum floodplain-management standards (47). However, it is estimated that less than 25 percent of individual owners of flood-prone property currently purchase flood insurance.

The participation of individual property owners nevertheless amounts to a considerable Federal financial liability. There are currently about 2.6 million flood policies in effect. These represent nearly $230 billion of insurance (22). The probable maximum loss in any given year has been estimated to be about $3.5 billion. More than 70 percent of NFIP policy holders are located in coastal communities. Those located in the most hazardous V-zones (some 65,000 policy holders) represent about 2.5 percent of the policy base (55); but between 1978 and 1992, these areas accounted for approximately 6 percent of total losses and 5 percent of all premiums.

Properties that existed before community regulations went into effect (i.e., pre-FIRM properties)[15] are eligible for subsidized premium rates nationwide. In the 1978-92 period, these properties represented about 80 percent of the NFIP's exposure while accounting for about 90 percent of the losses. Currently, about 42 percent of the NFIP's policies are subsidized. Subsidized businesses pay premiums that are, on average, one-third what the full-risk premiums would be. Through the 1970s and early 1980s, Congress supported heavy premium subsidies on existing construction in order to encourage broad-based participation of flood-prone communities in the program. Subsequently, subsidies have been reduced but not eliminated. The amounts of insurance that can be subsidized per policy are limited. In the case of single-family-structure coverage, this amount is $35,000. Protection above this is purchased at full-risk rates. About 19 percent of the $230 billion of insurance is subsidized.[16]

Historically, the NFIP has suffered from several problems and has been the subject of considerable criticism. Between 1978 and 1987, the program ran an average annual operating deficit of about $65 million, generating a $657 million deficit over that lo-year period (55). Beginning with FY 1986, however, the NFIP has been self-supporting. Rating and coverage changes made by the NFIP through the mid-1980s have enabled the program to build up reserves in years when losses were less than the historical average in order to help fund the program in years when greater-than-average losses occurred. Post-FIRM construction in general and post-FIRM construction in V-zones in particular have generated surpluses whereas pre-FIRM subsidized insurance has continued to be a drain on the National Flood Insurance Fund (74).

As of early 1993, the flood-insurance fund contained less than $40 million in reserves. This amount seems low when compared with potential flood-damage liabilities. FIA's estimates suggest that the probability is high of exceeding the existing surplus amount in any given year. As table 4-4 indicates, the probability that total annual losses will exceed $800 million nationwide is a high 30 to 35 percent, and the probability that losses will exceed $300 million per year is 60 to 70 percent (23). The FEMA director can borrow up to $500 million from the Treasury without notifying Congress, and an additional $500 million if Congress is notified. Thus, FEMA's present $1 billion borrowing authority is much less than its $3.5 billion probable maximum loss in any given year (23). FEMA estimates that its combined borrowing authority and annual

15 That is, properties that existed before the development of flood-insurance-rate maps, or FIRMs. Most communities had FIRMs by 1975.

16 H. Leikin, Federal Insurance Administration, personal communication, June 29, 1993.

Table 44-Estimated Probabilities of Exceeding Given Levels of Flood-Insurance Losses

Total annual loss costs ($ millions)	Probability of exceeding total annual costs (percent)
300	60-70
800	30-35
1,400	10-15
1,800	2-7
3,500	0,05-0.50

SOURCE Federal Emergency Management Agency (FEMA), "Estimating Probabilities of Exceeding Given Levels of Flood Insurance Losses in a One Year Period " (Washington, DC FEMA, Aug. 4, 1992)

premium income are adequate 85 to 90 percent of the time.[17]

The average annual cost of flood insurance per structure, as reported by FIA, is $296.[18] For full-risk policies in coastal high-hazard zones, it is over $800. Many homeowners would not consider these costs modest. Compared with the magnitude of potential liabilities under the program and the meager size of the current surplus, however, the current cost of insurance to property owners may not be high enough. Moreover, 86 percent of insured property owners in coastal high-hazard areas receive insurance at subsidized rates and pay about $440 less per year than those without subsidies. Premiums are still set to cover the average historical-loss year. Other possibilities would be to set the premium rate high enough to cover a catastrophic-loss year or, perhaps, to cover the loss associated with a 1 percent chance of occurrence in any year.

Another problem is that although flood insurance is mandatory for new construction that uses loans from federally insured banks, many lenders are not ensuring that the requirement is satisfied.[19] It has been estimated that there are between 8 and 11 million structures in flood-hazard areas, but fewer than 2 million are actually covered by flood-insurance policies (47). In Maine and Texas, for example, 22 and 78 percent, respectively, of properties in special flood-hazard areas that requested disaster assistance did not have insurance (87). In some cases, properties were erroneously classified and in others, insurance policies were allowed to lapse (87). Many properties in flood-hazard areas simply are not required by law to have flood insurance because they have no mortgage or because they have a mortgage from an unregulated lender (i.e., from a non-federally insured lender).

Repetitively damaged properties represent another problem for the NFIP. Over 40 percent of all flood-insurance claims have been for properties damaged more than once (87), yet FIA does not have the authority to cut off or substantially restrict future coverage for such properties. Individuals are permitted to rebuild and to continue to receive insurance, and the program allows for a potentially unlimited cycle of damage-rebuild-damage. Many believe that the premiums charged to repetitive-loss properties should be raised by FEMA to better reflect the risk of recurring flood damage (7).

Another significant concern about the way the NFIP functions in coastal areas is its failure to take into account long-term erosion. This amounts to a hidden subsidy of erosion risks because the flood program pays claims for erosion damage, although the risk is not a component of the rate structure for flood insurance.

Congress initiated changes to the definition of "flood" in 1973 to include collapse or subsidence along shorelines, and NFIP regulations were amended to allow creation of special erosion zones ("E" zones) and to mandate local land-management programs to take these hazards into account (59). Congress has not given FEMA the authority to map non-flood-related erosion zones (74), however, and property owners are generally opposed to erosion mapping. Also, FEMA has not

17 Ibid.

18 Ibid.

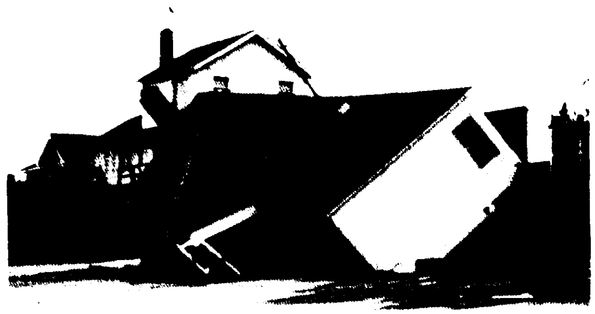
19 Legislation being considered in the 103d Congress (e.g., H.R. 62) addresses this problem.

sought to require local land-management programs (e.g., housing setbacks) to address erosion hazards, and long-term erosion trends are generally not taken into account in FEMA's current floodplain mapping. V zones are the flood zones closest physically to shoreline-erosion zones, yet they are often narrowly drawn, and "frequently exclude adjoining areas with virtually indistinguishable hazard characteristics" (59).

The NFIP plays a role in regulating reconstruction following a flood event. When a building is "substantially" damaged (e.g., more than 50 percent destroyed), it must be rebuilt in compliance with the local floodplain standards currently in force. Replacement of older, unelevated structures with newer, elevated buildings after disasters like Hurricane Andrew, for example, can have important mitigation benefits. However, flood policies do not pay for the increased cost of bringing buildings into compliance with newer standards. Thus, for example, more than 3,000 buildings in South Florida damaged by Andrew need to be elevated, but there is no insurance money available to do so. In addition, local governments may choose to apply the ' 'substantially damaged" standard only if damages are greater than 50 percent of the replacement value of the structure. This has the effect of exempting more damaged structures from elevation and floodplain-management requirements when rebuilding.

FIA would like to provide "increased cost of construction coverage' but needs authority from Congress to do so (74). Such coverage, on average, would cost property owners an extra $34 annually. In coastal high-hazard zones, however, the additional premium would be substantially more, especially for subsidized property owners.

Finally, flood-insurance maps are infrequently revised and updated. FEMA is able to remap communities every 9 years, on average. However, many participating communities are growing rapidly, and development in the floodplain can substantially modify local flood hazards in less time than that.



STEPHEN LEATHERMAN

A house tumbles onto the beach at Fire Island, New York, as a result of erosion damage caused by the December 11, 1993, northeaster.

■ Federal Disaster Assistance

The Federal Government has been involved for many years in assisting State and local governments in responding to, and recovering from, national disasters. Its primary authority for providing disaster relief is the Robert T. Stafford Disaster Relief and Emergency Assistance Act of 1974 (P.L. 93-288, as amended by P.L. 100-707). Such assistance has, as it should, enabled communities to rebuild centers of commerce after disasters and to return (more or less) to pre-disaster conditions. However, although financial assistance to people who have suffered a major misfortune is often appropriate, it can also subsidize risky public and private actions and thus function as another form of incentive for hazardous coastal development.

Disaster assistance available through FEMA generally falls into two categories: individual and family assistance, and public assistance. Under FEMA's Individual and Family Grants (IFGs) program, grants upto$11,500 (adjusted annually for inflation) can be made to individuals and families to cover disaster-related expenses (e.g., home repairs not covered through insurance and replacement of personal belongings) .[20] Under FEMA's public-assistance program, States and communities can receive grants (usually at a 75 percent Federal cost share) to cover the cost of damages to public facilities. Eligible projects include repair of roads, bridges, sewer and water systems, recreational facilities, and public boardwalks, and, if certain beach-maintenance eligibility criteria are met, renourishment of beaches. Communities not participating in NFIP, however, receive reduced amounts of public assistance. Applicants under the IFG program need not be in a participating community nor have purchased Federal flood insurance, though they must agree to purchase flood insurance as a condition of receiving an IFG grant.

Precisely how much of an impact Federal disaster assistance has in encouraging (or failing to discourage) hazardous and damaging coastal development is uncertain Amounts of Federal disaster assistance in recent years have been substantial. Some $8.3 billion was spent between 1978 and 1988 on presidentially declared disasters. FEMA reports that approximately $89 million per year was spent as a result of hurricanes and coastal-storm events during this period (55). These disaster-assistance monies provide a significant subsidy for coastal communities, underwriting various potentially risky coastal public investments. In several recent disasters, including Hurricanes Andrew and Hugo, the Federal Government agreed to cover 100 percent of the costs of eligible public-sector damages. Where the 25 percent cost sharing has been required, the State frequently assumes half of that, leaving local governments to assume only 12.5 percent of the cost of such damages.

There are currently no provisions in this system for considering the magnitude of the damage to an individual community or the financial capability of the State or local government to cover these damages. High-risk communities would have stronger incentives to ensure that public facilities are placed in safe locations or designed in ways that minimize future vulnerability to hurricanes or other disasters if such factors were considered. In many cases, the Federal reconstruction subsidy is in addition to the original Federal subsidy used to construct the facility.

Disaster assistance has in many ways been seen by States and communities as an entitlement that is deserved regardless of the extent or cause of the damages, the ability of these jurisdictions to assume the costs, or participation in the NFIP. In theory, Presidential disaster declarations are only to be issued when the resources of affected State and local governments are clearly exceeded. Yet, Presidential declarations (which average 20 to 25 annually; 46 were proclaimed in 1992) are increasingly viewed as pro forma and have occurred even where damage levels are relatively modest and where State and local governments could clearly have assumed the cost with little burden. (A Presidential disaster declaration was made after Hurricane Diana struck the North Carolina coast in 1984, for example, even though the $79 million in damages was relatively small and the State could have handled the damages.) One survey of 481 communities found that local officials believe they can handle losses much larger than those defined by FEMA as constituting a disaster (1 1).

FEMA has sought to reform this system in the past, only to be criticized by representatives of State and local governments and owners of property in high-risk areas. In the mid-1980s, for example, FEMA proposed that the required State and local share of public-assistance grants be increased to 50 percent (i.e., 50 percent Federal, 50 percent State and local) and that a set of criteria be imposed to determine a legislative entity's ability to pay. These proposals met with considerable political opposition and were eventually dropped. Many commentators, however, have echoed the need for such reforms, which might

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[20] IFG grants are available only to people who do not qualify for low-interest Small Business Administration disaster loans.

The San Francisco sea wall.

Beach-nourishment project at Rockaway, New York.

help to promote implementation of State mitigation measures (10, 25).

In addition to FEMA, several other Federal agencies provide some form of disaster assistance. These include loans, grants, and reconstruction monies from the independent Small Business Administration and Economic Development Administration, the Department of Transportation's Federal Highway Administration (for roads and bridges), the Department of Education (for school buildings), the Department of Agriculture's Farmers Home Administration., and the Army Corps of Engineers. In all, there are some 30 Federal disaster-relief programs (5).

One effort to coordinate the actions of the different Federal agencies was the Interagency Hazard-Mitigation agreement signed in 1980. Under this agreement, an interagency hazard-mitigation team is called into action immediately after a disaster declaration and is required to prepare a report within 15 days of the declaration. These reports typically identify hazard-mitigation opportunities and contain recommendations, many of which have been pursued by FEMA and other Federal agencies. These recommendations also typically are considered in the Section 409 hazard-mitigation plans prepared by States (see below). No systematic evaluation of how recommendations in these reports are implemented has yet been done.

Federal Beach Nourishment and Shoreline Protection

Shoreline protection, either in the form of "hard" devices, such as seawalls, revetments, groins, jetties, and breakwaters, or as "soft" buildup or replenishment of beaches and dunes, is often justified where storm surges and/or erosion threaten well-developed coastal communities and expensive facilities like harbors and resorts (59). The best protective measure for a given site will depend on the underlying physical conditions at the site and on economic, social, and environmental costs (see box 4-B).

The Federal Government, through the Army Corps of Engineers, has subsidized shore-protection projects for decades. Where the benefits of shoreline protection are associated with improving recreational opportunities or counteracting erosion, the Federal share of approved projects is currently 50 percent. Where the benefits include prevention of physical damage to property, the Federal share of construction costs increases to 65 percent. Most projects are now justified on the basis of prevention of physical damages, The periodic renourishment that maybe required on some beaches after a project has been

Box 4-B-Protect or Retreat?

There are essentially two types of responses to erosion and sea level rise: protect vulnerable areas or retreat from the coast. The most appropriate response for a specific area will depend on an array of socioeconomic and environmental factors, including the number and value of coastal structures at risk, the relative cost of protection and retreat options, aesthetic values, and the value of preserving undeveloped areas (49). The appropriate response will also depend on physical conditions at the site, including the availability and suitability of sand.

Protection can mean either building defenses that "harden" the shoreline against incursions of these% or replacing eroded beach sand, as necessary, through *beach nourishment* or *replenishment*. Since 1946, the U.S. Army Corps of Engineers has undertaken 121 shore protection projects encompassing a total shoreline distance of just over 300 miles (460 kilometers).[1] Another 52 projects that would protect about 230 miles of coast have been authorized (but not yet funded) by Congress (66). About 75 percent of all Corps projects involve beach nourishment as a basic feature, although beach nourishment is sometimes used in combination with hard structural protection measures (91).

The number of miles devoted to beach and dune nourishment in Corps projects reflects a general community preference for nonstructural approaches where feasible. Such approaches are especially preferable where beaches are primary assets for coastal communities, as, for example, in Miami Beach, Florida. Beach nourishment projects can also be expensive, but costs are site-specific and highly variable. In Miami Beach, nourishment of a 10.5-mile stretch of coast cost about $6 million per mile in the late 1970s. Beach nourishment can be an effective protective measure because beaches are efficient in absorbing wave energy. Usually, beach nourishments used where erosion of a natural beach is occurring. The ability of the nourished beach to absorb wave energy may, thus, come at the expense of its own erosion, so periodic renourishment maybe required. As an adaptation to sea level rise, beach nourishment has the advantage that it can be abruptly halted (e.g., in favor of retreat) without abandoning large investments when the costs of continued nourishment exceed benefits.

Some beach-nourishment projects have been criticized for having life spans that are shorter than anticipated and, more generally, for falling to perform as designed (66). Debate continues on the performance of specific beach-nourishment projects (e.g., see ref. 39). However, it seems clear that as understanding of fill and sediment dynamics has advanced, the performance of such projects has improved (39).

Hard structural protective measures are also appropriate in some circumstances. The most common are sea walls, breakwaters, and groins. Sea walls are concrete, steel, stone, or timber structures built parallel to and on the landward side of beaches. Their primary purpose is to protect upland areas. Like nourishment projects, they are normally built in areas that are eroding, and thus beaches in front of sea walls may eventually disappear. However, properly designed sea walls can protect the land behind them without causing adverse effects to beaches (59). Sea walls are initially more expensive than beach-nourishment projects, but the periodic costs required of beach-nourishment projects are not incurred. Some sea walls will likely have an adverse effect on the ability of wetlands to migrate in response to sea level rise. A 20-inch (0.5-meter)[2] rise in sea level could result in the loss of35 percent of coastal wetlands if standard measures are taken to protect currently developed lowlands; however, 30 percent of wetlands could be lost in any case if no protective measures are taken (62).

Breakwaters are linear structures placed in nearshore waters whose purpose is to shield the shoreline from incoming wave energy. Groins are wall-like structures constructed perpendicular to the shoreline and used to trap sand moving parallel to the shore. They are usually used in combination with beach nourishment. They have often been improperly used in the past, resulting in downdrift beach erosion.

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1 To convert miles to kilometers, multiply by 1.609.

2 To convert inches to meters, multiply by 0.025.

In coastal cities and seaside resort communities, the value of the land is usually great enough that decisions to install hard structures or replenish beach sand are often made. Retreat is usually not a practical alternative in these areas. In sparsely developed areas, the opposite is generally the case, and retreat maybe the only feasible option (83). Gradual retreat from the coast, limiting coastal uses to those that can be accommodated without protection, is favored by many insurance companies and environmentalists as the ultimate solution to coastal erosion and sea level rise. They argue that protection measures can only forestall inevitable destruction and, if risky development is allowed to continue, increase the costs of protection and retreat (54). Policies that promote retreat include setback provisions that some coastal States have adopted and the Federal Government's flooded-properties-purchase program and UptonJones relocation-assistance program (see main text).

A substantial amount of money has been invested in coastal areas. Owners of beachfront property are understandably upset when their homes or businesses are threatened by erosion, and retreat to a safer site may not be an option for many. The reality of erosion and sea level rise creates some difficult public-policy issues. Property owners naturally want to take steps to protect threatened iand. However, in some instances (e.g., in some quickly eroding areas), it will probably not be desirable or economically justified from a community or national perspective to do so, and gradual retreat will be preferred. Two issues with immense consequences for coastal development are likely to continue to be debated. First, is the extent to which private-property owners should be subsidized by taxpayers at large to maintain risky coastal development. Second, is how much property owners should be compensated when a State limits the economic use of seaside property. These issues will become more controversial as the amount of money invested in coastal development increases. The possibility of future sea level rise suggests that clear policies guiding the expectations of property owners need to be established.

SOURCE: Office of Technology Assessment, 1993.

completed (see box 4-B) has not to date been considered a "maintenance activity' (if it were, the Corps would not be involved), so these recurring costs are subsidized as well.[21] If the Corps uses sand dredged from navigation projects for beach nourishment, the Federal Government currently provides 50 percent of the increased costs that would be incurred to place this sand on beaches rather than to dispose of it in the least costly manner. Finally, the Federal Government shares the costs of feasibility studies with States. Federal aid is usually recommended to continue through the life of the project, normally 50 years for hard structures (91).

In recent years, the Corps has spent between $40 and $70 million annually for beach nourishment and structural-protection measures, the majority of which has been for beach nourishment.[22] Because the largest benefit of beach-protection projects is realized at the local or regional level, it may be desirable to shift more of the burden of paying for such projects from the Federal Government to the States. Responsibility for maintaining beach-nourishment projects, in particular, could be shifted to affected States, just as is maintenance of Corps-built flood-control projects.

States have also been active in assisting with and subsidizing shore-protection efforts. Several States now provide funding, often through the issuance of bonds, for local renourishment programs, and often in combination with Federal subsidies. In South Carolina, for instance, the State legislature created a $10 million Beach Renourishment Fund in 1988, most of which went to emergency renourishment and dune-rebuilding projects after Hurricane Hugo (43). Likewise, the

21 L. Vallianos, Institute of Water Resources, U.S. Army Corps of Engineers, personal communication, July 1993.

22 J. Housley, U.S. Army Corps of Engineers, personal communication, July 1993.

State of Maryland has provided about $60 million under its Shore Erosion Control Program (SECP) for beach renourishment in Ocean City. The State also provides interest-free loans and technical assistance for shorefront property owners experiencing erosion problems, and 50 percent matching funds to property owners who undertake nonstructural erosion-control measures such as planting grass (68). The State of New Jersey recently passed a bill to appropriate $15 million per year for shore projects, including beach nourishment.

U.S. Tax Code

Several major coastal-development subsidies are also available in the U.S. Tax Code. The casualty-loss deduction allows coastal property owners to deduct the cost of uninsured damages resulting from hurricanes and other natural disasters. Allowable deductions are determined by subtracting the post-storm value of property from its pre-storm value, less insurance received.[23] The deduction is only allowed where losses exceed 10 percent of adjusted gross income.

Other U.S. Tax Code subsidies include interest and property-tax deductions for second homes (which comprise much of coastal development) and accelerated depreciation for seasonal rental properties. These types of subsidies are largely hidden, and estimates of their aggregate cost are hard to come by. There is little doubt, however, that the extent of implicit public subsidy is substantial.

Other Development Subsidies

Coastal growth is subsidized by a variety of other Federal development programs and grants. The Farmers Home Administration, for example, provides subsidies in the form of community-facility loans, business and industry loans, and rural housing loans (88). The Department of Housing and Urban Development provides guaranteed home loans, as does the Department of Veterans Affairs. The Rural Electrification Administration provides loans for development of electrical systems, and the Environmental Protection Agency has provided considerable funding for water systems and for wastewater treatment. Extensive funding for the construction of highways, roads, bridges, and other improvements that make many otherwise remote coastal areas readily accessible has been provided by the Department of Transportation and is one of the more significant factors affecting the development of barrier islands. Most of these development-related grants and subsidies are not limited to coastal areas, and estimates of their magnitude and of their impacts in coastal regions are not available.

OBSTACLES TO BETTER MANAGEMENT

Improvements in the Federal and State programs that affect development in the coastal zone are possible and, considering the potential for increasing vulnerability in coastal areas as a result of global climate change, desirable. However, several impediments to reducing risk exist. Among these are the fact that people continue to be attracted to coastal areas, the notion of subsidies as social entitlements, private-property concerns, the cost of change, and institutional fragmentation and regulatory obstacles.

The Attraction of Coastal Areas

The economic and personal attraction Americans have to coasts can be seen as an obstacle to many coastal-management reforms. Recent surveys of coastal-property owners suggest that many have a solid appreciation for the danger and riskiness of building and living in coastal areas, but see hurricanes and coastal storms as simply a necessary part of the tradeoff for the benefits of coastal living (6). Table 4-5 shows the results of a questionnaire mailed to owners of beachfront

23 See note 455 on Stem, hurricanes, and floods in 26 U.S. Code ('U. S. C.) 165.

Table 4&Results of a Mail Survey of 132 Owners of Beachfront Property in South Carolina After Hurricane Hugo That Asked the Question:

"Now that you *have experienced* the effects *of a hurricane, has this had any influence on your feelings about owning beachfront property?"*

	Percent
1. Yes, would not buy beachfront property again	6
2 Yes, would like to sell my property and buy property in a safer location	7
3. No, hurricanes are just a normal risk in beachfront areas	39
4. No, the benefits and enjoyments of beachfront living outweigh the potential risks	42
5. Other	6

SOURCE: T. Beatley, *Hurricane Hugo and Shoreline Retreat: Evacuating the Effectiveness of the South Carolina Beachfront Management Act,* final report to the National Science Foundation, September 1992

property in South Carolina heavily damaged by Hurricane Hugo. Even those who were devastated by such events did not generally have regrets or plan to move to safer locations. A related obstacle is the economic advantage of beachfront locations. Owners of beachfront property maybe reluctant to relocate structures at risk until they have nearly collapsed into the surf because the income from renting these units on the beach is substantially higher than it would be on sites farther inland. Also, equivalent beachfront property is often unavailable or too expensive.

Coastal Subsidies as Social Entitlements

Some coastal subsidies have, over time, acquired a constituency and set of beneficiaries who tend to view them as social entitlements, in much the same way that people view social security. Similar views exist about disaster assistance. Almost regardless of the magnitude of the damages or the ability of States, localities, and property owners to assume the damages, many people perceive that a disaster declaration and disaster assistance are deserved. Taking away or Curtailing programs such as Federal flood insurance would be opposed by communities and coastal property owners who fear that property values, salability, and economic attractiveness of coastal areas would be reduced.

Private Property and the Takings Issue

A major impediment to more-effective and more-sensible coastal management is concern about impacts on private property. Specifically, property owners who are restricted as a result of coastal-management programs (e.g., Ocean-front setback requirements or restrictions on filling wetlands) may claim that these restrictions represent unconstitutional *takings* of private property under the fifth amendment to the U.S. Constitution (as well as under similar provisions in State constitutions). If land-use regulations are so restrictive that they deny all reasonable economic use of a coastal property, the courts may well conclude that a taking has occurred.

A recent case in South Carolina, *Lucas v. South Carolina Coastal Council,* illustrates the potential dimensions of this obstacle.[24] David Lucas, a South Carolina developer and property owner who had acquired two small lots on Isle of Palms (a barrier-island community east of Charleston), was prevented from building on them as a result of the 1988 South Carolina Beachfront Management Act (both lots were seaward of the so-called "baseline") (69). Arguing that the setback restrictions deprived him of all reasonable economic use of his property, he challenged the restrictions as an unconstitutional taking. The lower court found in his favor and awarded him

[24] 112 S. Ct. 2886, 1992. See also reference 69.

$1.2 million. The South Carolina Supreme Court overruled this decision, upholding the Coastal Council's actions as merely preventing a public harm and thus not requiring compensation. Lucas appealed to the U.S. Supreme Court, where the majority determined that some compensation should be paid when the value of property is essentially destroyed by regulation. The court reiterated the position that when land-use regulations that preclude all economic use of property go into effect, a taking might occur (unless the regulation serves only to enforce a preexisting common-law doctrine, such as nuisance law). The case was then returned to the South Carolina Supreme Court, which, in reconsidering, found that a temporary taking had occurred. In July 1993, a settlement was finally reached, and the State agreed to pay Lucas $1.5 million.[25] The full implications of the Lucas decision remain to be seen, but it will likely be cited by opponents of more-stringent coastal land-use regulations.

Takings law is still developing, and considerable disagreement exists about when a regulatory taking actually occurs. What constitutes a reasonable economic use, for example, remains a debatable question. The South Carolina law did not prevent the erection of a temporary structure on the Lucas property, or prohibit the sale of the lots to adjoining property owners. The use restrictions in the NFIP generally are not considered a taking because participation by communities is voluntary and because protecting people from the threat of harm is part of community authority under police powers.

Irrespective of the specific constitutional challenge of a taking, additional restrictions on the use of land have in recent years met with serious political opposition. Several property-rights-protection groups, such as supporters of the wise use movement in the West., have been established and have been vocal in opposing additional government restrictions (see vol. 2, ch. 5).

Cost of Change: Perceived and Actual

Potential cost—actual and perceived-represents an obstacle to many proposed program changes. Coastal-land acquisition, for example, may entail major expenditures, given the high price of coastal property. Public subsidies for relocation of vulnerable structures could also involve substantial public expense. On the other hand, some alternatives are relatively inexpensive, and their perceived costs may be much higher than their actual costs. Adoption of coastal building standards, for instance, actually involves a relatively small increase in the cost of home construction (l).

In addition, attention is frequently focused on the initial costs of programs without considering the resulting long-term cost reductions. Although relocation subsidies (e.g., the Upton-Jones relocation assistance, discussed below) may involve substantial upfront costs, they serve to curtail future-loss expenditures, sometimes on properties that would likely be damaged again. Similarly, public acquisition of wetlands, floodplains, and other sensitive coastal lands, although expensive initially, can serve to prevent future public costs that could be many times higher (e.g., costs of disaster relief and ecological damages).

Institutional Fragmentation and Regulatory Obstacles

An important obstacle to better management, especially at the Federal level, is institutional (or organizational) fragmentation. No single Federal agency or department has responsibility for coastal management and coastal-damage risk reduction. For example, the Coastal Zone Management program is administered within the National Oceanic and Atmospheric Administration (NOAA); responsibility for wetland management is shared by the Environmental Protection Agency (EPA), the Corps of Engineers, and many others (see vol. 2, ch. 4); FEMA has responsibility for flood

[25] South Carolina intends to recoup its money by selling the lots for development. However, the new build.@ permit will stipulate that the owner must remove structures that ever flood or become seaward of the dunes because of beach erosion (50).

insurance; and several agencies and offices are involved in disaster assistance. These different Federal programs and initiatives are not well-coordinated and there is no unified, comprehensive strategy for reducing the risks of living on the coast or for addressing specific issues such as climate-related sea level rise. Moreover, the perceived missions of these different agencies vary considerably, and can result in actions and programs that work at cross-purposes. FEMA has historically seen its mission not in terms of coastal management, but in terms of helping families and communities respond to, and cope with, natural disasters.

Hazardous coastal development is caused, in part, by an inadequate regulatory and enforcement framework. Many coastal States and localities have minimal controls on the location and quality of development. Although some States have adopted fairly stringent coastal setback requirements, for example, many others frequently permit new development close to the ocean front and in locations subject to erosion threats. North Carolina requires major coastal structures to be set back 60 times the average annual erosion rate (61). Yet, South Carolina effectively has no fixed shoreline setback, and through a special permit procedure, allows development very close to the ocean.

Few coastal States or localities prohibit development within floodplains, although structures in these areas may be subject to certain design requirements, such as being elevated to or above the 100-year flood level. To the uninformed coastal resident or buyer of coastal property, securing a State or local permit maybe falsely perceived as a "certification' of the safety of a coastal site or location. Moreover, ensuring full community compliance with existing floodplain-management regulations is difficult because FEMA's enforcement and monitoring staff is small.

The extensive wind damage from Hurricane Andrew illustrates the looseness with which many development codes have been implemented and enforced. The South Florida Building Code (with a wind-design standard of 120 miles (190 kilometers)[26] per hour) was generally viewed as one of the most stringent performance-based building codes in use anywhere. Yet, problems with enforcement and implementation (and with the provisions of the code itself) have raised questions about the stringency and effectiveness of coastal regulations. A grand jury in Dade County recently issued a report extremely critical of the "shoddy" building practices evident in South Florida (8). Among the problems cited by the grand jury were inadequate and lax building inspection, inability to control untrained and unlicensed building contractors, and corruption, apathy, and high turnover in the Florida Building and Zoning Department. Strengthening the code (including changing the ways roof systems are constructed) and increasing Federal wind standards for mobile homes (most of which were destroyed in the hurricane) were recommended.

In many coastal areas, building codes are simply not required. In 12 coastal States, adoption of building codes is left entirely up to local officials (53). In South Carolina, for instance, local governments are under no requirement to adopt a building code (although if they choose to do so, it must be the State's standard building code). In Texas, no State building code is mandated, and counties do not even have the authority to adopt building codes if they wanted to-leaving many rural and unincorporated areas without any construction standards.

ENCOURAGING LESS-DAMAGING COASTAL-DEVELOPMENT PATTERNS

The existing policy framework does include several major programs and policies that seek to reduce the risks of living on the coast and that could serve as the foundation for policy changes in the future. As mentioned earlier, the NFIP has

26 To convert miles per hour to kilometers per hour, multiply by 1.609.

mandated, from its beginning, the adoption of certain minimum standards for floodplain management. In recent years, the program has been giving much greater attention to risk reduction and hazard mitigation. Some relatively recent changes to the NFIP, discussed below, include the Section 1362 Flooded Properties Purchase Program, the Upton-Jones relocation-assistance program, and the Community Rating System. Recently, several bills introduced in Congress have proposed further reforms, and these initiatives are described here as well. Other programs that have positively encouraged mitigation and risk reduction (or have the potential to do so) include the Federal Hazard Mitigation Grants program (Section 404 of the Robert T. Stafford Disaster Relief and Emergency Assistance Act), State hazard-mitigation plans (required by Section 409 of the Stafford Act), the Coastal Barrier Resources Act (COBRA; P.L. 97-348), the Federal Coastal Zone Management Act (CZMA; P.L. 92-583), and the State coastal-management programs through which the Federal CZMA is implemented.

Section 1362 Flooded Properties Purchase Program

The NFIP, despite some limitations, has improved gradually over the years, and certain programs and provisions have been developed that move it in the direction of greater hazard mitigation and loss reduction. One of these is the Section 1362 Flooded Properties Purchase Program. Authorized in 1968 by a section of the National Flood Insurance Act, the program allows FEMA to break the damage-rebuild-damage cycle that accounts for many damage claims.

Under the program, FEMA can offer to buy out owners of damaged property, paying the difference between the fair market value of the structure and the allowable insurance claim, plus the value of the land on which the structure is or was located. The community must agree to participate, must be willing to accept the land, and must prepare a plan for its use that ensures that it will never be developed in the future. Eligible properties must have had Federal flood insurance and must meet one of several damage criteria (e.g., be damaged substantially beyond repair).

The Section 1362 Program has been used sparingly: since first funded in 1980, FEMA has acquired only about 100 properties per year. Modest amounts of funds are set aside for Section 1362 purchases, and there seems to be a bias against using those funds in coastal areas; because land in coastal communities is often very expensive, it is usually possible to get a greater "bang for the buck" when these limited funds are used along rivers. Since 1980, Congress has appropriated less than $5 million per year for Section 1362 funds, and in some years, FEMA has not spent it all.

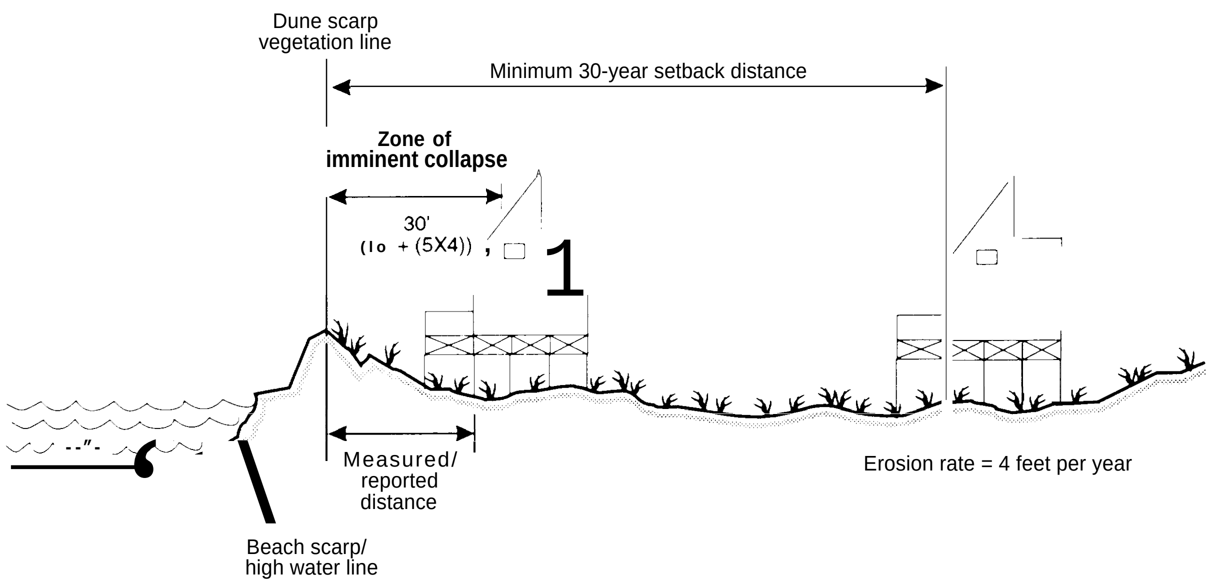
Upton-Jones Relocation Assistance

Another major change in the flood-insurance program was passage of the so-called Upton-Jones Amendment. An amendment to the Housing and Community Development Act of 1987 (P.L. 100-242), this provision sought to make available funds for subsidizing the demolition or relocation of shoreline structures that are subject to fairly immediate erosion hazards. Under the NFIP prior to Upton-Jones, a property owner could not receive any flood-insurance payment until the structure was actually damaged.

Under Upton-Jones, owners of shorefront property with Federal flood insurance are eligible for sizable demolition or relocation subsidies. Specifically, the amendment provides up to 40 percent of the insured value of a building for relocation (or 40 percent of the cost of relocation, if less) and up to 110 percent of the insured value of a structure for demolition. Relocation funds can be used for, among other things, new site preparation, construction of a new foundation, and utility hook-ups.

To qua.ii@, structures must be within a zone *of imminent collapse. FEMA* defines this area as

Figure 4-5--FEMA's Criteria **for Imminent-Collapse and Setback Determinations Under the Upton-Jones Amendment**



NOTE: To convert feet to meters, multiply by 0.305.

SOURCE: National Research Council, *Managing Coastal Erosion* (Washington, DC: National Academy Press, 1990).

seaward of a line 10 feet plus 5 times the average annual rate of erosion, as measured from a reference feature such as the normal high-water line (fig. 4-5). The provisions also require the State or local government to condemn structures or certify that they are in danger of collapse. Once FEMA declares a structure subject to imminent collapse, the owner has a certain reasonable time to relocate or demolish it, after which only 40 percent of losses can be recovered in the next storm or flooding event.

Once demolition or relocation occurs, certain restrictions are placed on the availability of new insurance. Specifically, to receive flood insurance, any future development on the property must be located landward of the 30-year erosion line for structures with one to four dwelling units or landward of the 60-year line for larger structures. Structures moved to a different site must also meet these and whatever other floodplain-management restrictions are in effect in the new location.

To date, use of the Upton-Jones Amendment has been limited. As of April 1992, only 494 claims had been filed. Of these, 283 were approved, 217 for demolition and 66 for relocation. The average value of demolition claims has been more than twice that of relocation claims (79). Low participation can be explained in part by a general lack of awareness about the program, a reluctance to remove or interrupt income from rental properties, a lack of suitable or affordable relocation sites, and problems encountered in condemning structures (e.g., many States do not allow condemnation unless there is actual structural damage (59)).

Despite considerable support for the concept, the Upton-Jones Amendment has not decreased NFIP expenditures or induced voluntary, anticipatory action by owners and has been insufficient to overcome individual and market incentives for ocean-front owners to remain on the coastline (17, 18, 56). The National Research Council has recommended that relocation be encouraged over demolition, relocation behind the 30-year erosion line be mandated, easements or some other form of legal restriction preventing use of vacated shorefront areas be required, and insurance be terminated or premiums raised for structures within the zone of imminent collapse that are not relocated or demolished after a certain time (59).

The Upton-Jones program could be criticized as underwriting private risks because it encourages risky coastal development if property owners expect relocation assistance in the future (7). Also, the program applies only to individual properties: Upton-Jones provisions can be used to relocate one structure even as another one is being built on an adjacent, eroding site. The suggested changes mentioned above, in addition to coupling program benefits to more stringent erosion management for new construction (e.g., coastal setbacks), would serve to substantially eliminate such incentives.

Community Rating System

FEMA has recently initiated a program, the Community Rating System (CRS), to reward communities for the additional activities and programs they undertake to minimize flood damages beyond the minimum requirements of the NFIP. Specifically, the insurance premiums of property owners within communities that undertake flood-damage-reduction activities are reduced based on the extent of eligible activities undertaken. CRS gives credit for 18 mitigation activities, grouped into four categories: public information, mapping and regulations, flood-damage reduction, and flood preparedness (see table 4-6). Points are assigned to activities depending on the extent of their implementation within the community and their likely effectiveness at achieving CRS objectives (24).

Points allocated to individual measures are added to produce the community's total points, which are then used to determine the extent of premium reduction for property owners. As table 4-7 indicates, premium reductions range from 5 to 45 percent for property within Special Flood Hazard Areas (i.e., A and V zones). A maximum 5 percent reduction is allowed for property outside Special Flood Hazard Areas, largely because premiums are already low in these areas and because the measures for which credits are given are directed at the 100-year-flood zones.

The numbers of communities participating in the CRS program have so far been modest. In FY 1993, only 565 communities took part (3 percent of those participating in the NFIP). This small percentage, however, does represent about 45 percent of the flood-insurance-policy base. The level of mitigation effort for most participating communities has been relatively low, with the vast majority of communities (about 78 percent) eligible for only a 5 percent reduction in policyholder premiums. Another 15 percent of communities are eligible for 10 percent reductions. Twelve communities were given reductions of 15 percent, and one qualified for a 25 percent reduction.[27]

Questions nevertheless remain about the CRS strategy. It is not clear whether the most active local governments would not be undertaking these kinds of mitigation actions, anyway. Some of the measures for which local governments are given credit, such as hazard disclosure, may not lead to clear hazard or damage reduction. Conversely, credits are not now given for some measures, such as erosion management, that might be desirable. The CRS approach could also be criticized for further reducing premiums paid in hazardous areas. As an alternative, several of the measures for which localities are given credit (e.g., erosion setbacks) could simply be made mandatory as conditions for participating in the NFIP.

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27 Data on the Community Rating System provided by C. Keegan, Federal Emergency Management Agency, Jan. 3, 1993.

Table 4-6--Community Rating System Designed by the Federal Emergency Management Agency to Encourage Communities to Minimize Flood Damage

Activity	Maximum points allowed	Average points earned	Percent of applicants requesting credit
Public information			
Elevation certificates	1 37[a]	73	100
Map determinations	140	140	92
Outreach projects	175	59	53
Hazard disclosure	81a	39	40
Flood-protection library	25	20	77
Flood-protection assistance	66	51	45
Mapping and regulations			
Additional flood data	360[a]	60	20
Open-space preservation	450[a]	1 15b	42
Higher regulatory standards	785'	101 [a]	59
Flood-data maintenance	12oa	41	41
Storm-water management	380[a]	121	37
Flood-damage reduction			
Repetitive-loss projects	441 [a]	41	11
Acquisition and relocation	1,600	97	13
Retrofitting	1,400	23	3
Drainage-system maintenance	330'	226	82
Flood preparedness			
Flood-warning program	200[a]	173	5
Levee safety	900[a]	0	0
Dam safety	120[a]	64	45

a Maximum Points revised since the 1990 community Rating System schedule.
b 1990 credits revised to reflect the 1992 Community Rating System schedule.

SOURCE. Federal Emergency Management Agency (FEMA), Interagency *Hazard Mitigation Survey Team Report on the Northeaster Storm,* FEMA 973-NJ-DR (Washington, DC: FEMA, January 1993)

Hazard-Mitigation Programs and Requirements Under the Stafford Act

There have also been some reforms in the Federal disaster-assistance framework in recent years. The 1988 amendments to the Stafford Act created a Hazard Mitigation Grant Program (HMGP) (Section 404), which provides Federal matching funds for 50 percent of individual State and local mitigation projects. The grant funds are tied to disaster declarations and are limited to 10 percent of the total Federal share of the public-assistance monies made available for permanent restorative work.

FEMA had approved 206 applications for hazard-mitigation grants through 1992, obligating approximately $43 million. As table 4-8 indicates, these funds have been used to finance various types of mitigation, including improving public-private facilities (e.g., floodproofing sewage treatment systems), constructing drainage systems, purchasing equipment, relocating structures, developing planning programs, promoting education and training activities, and improving land. Nearly 60 percent of the funds were used for improvements to public-private facilities. Only about 11 percent of these grants were used for relocation or acquisition, and only about 3 percent

Table 4-7—Premium Reductions for Special Flood Hazard Areas (SFHAs) and Non-SFHAs in the Federal Emergency Management Agency's Community Rating System

Points earned	Class	SFHA premium reduction (percent)	NonSFHA premium reduction (percent)
4,500+	1	45	5
4,000-4,499	2	40	5
3,500-3,999	3	35	5
3,000-3,499	4	30	5
2,500-2,999	5	25	5
2,000-2,499	6	20	5
1,500-1 ,999	7	15	5
1,000-1 ,499	8	10	5
500-999	9	5	5
0-499	10	0	0

SOURCE Federal Emergency Management Agency (FEMA), National *Flood Insurance Program Community Rating System Coordinators Manual* (Washington,DC: FEMA, July 1992.

Table 4&—Rank of Project Categories by Dollar Amount and Percent of Estimated Obligations in the Hazard Mitigation Grant Program (January 1989 to August 1992)

Type of project	$ Millions[a]	Percent
Public-private facilities	**25**	**58**
Drainage projects	6	14
Equipment purchases	5	12
Relocation of structures	5	11
Planning products	1	3
Education and training	<1	1
Land Improvements	<1	1
Total	43	100

[a] 1992 dollars

SOURCE. Joint Task Force on the Hazard Mitigation Grant Program, The Hazard Mitigation Grant *Program." An Evaluation Report,* prepared by National Emergency Management Association, the Association of State Floodplain Managers, and the Federal Emergency Management Agency, September 1992

for planning programs, such as development of beach-management plans, hazard-mitigation plans, and zoning- and building-code ordinances (41).

A joint task force of the National Emergency Management Association and the Association of State Floodplain Managers was formed to evaluate HMGP. Among the concerns identified were the slow pace of implementing the program, the lack of "hazard mitigation principles and guidance, ' difficult.ies in State-level coordination, and the failure of States and localities to identify mitigation opportunities before a disaster occurs. The specific recommendations of the joint task force include: creating State teams to respond to disaster declarations; developing and endorsing a Federal-State hazard-mitigation strategy after each disaster declaration to identify mitigation opportunities; updating and refining State hazard-mitigation plans through the Federal-State agreement; strengthening technical-assistance activities (e.g., through training and publication of handbooks); and improving guidance on project eligibility (41). Of special importance are the task force's conclusions that FEMA should better enforce State hazard-mitigation-plan requirements and seek to elevate the priority and importance given to these plans. Land use, relocation, and nonstructural programs are perhaps underrepresented in the HMGP. The overall level of funding seems modest, but not all available funds have been obligated because too few eligible projects have been proposed.

The Stafford Act also made mitigation an eligible expense under the FEMA public-assistance program (Section 406), and thus allows the Federal Government to contribute 75 percent of the funds for reconstruction improvements to the infrastructure (e.g., roads, bridges, and utility lines) to make them less vulnerable to future damage. Before these changes were made, mitigation expenditures were not eligible for public assistance, and if State and local governments wanted to rebuild damaged infrastructure to higher standards, they had to bear the entire expense. Section 406 could be more useful to States than the Hazard Mitigation Grant Program because opportunities for mitigation can be identified and taken advantage of quickly during the damage survey process, the mitigation can be incorporated into reconstruction without having to go through a grant-review process and compete with other projects, and the amount of money available is not limited by the 10 percent cap of the Federal share of public-assistance monies.

The existing Federal disaster-assistance framework does have some significant "teeth' for promoting and requiring hazard mitigation. Section 409, although rarely used, states that the President may make disaster assistance conditional on State or local actions to mitigate hazards ("including safe land use and construction practices"). In addition, States receiving disaster assistance are required to prepare a State hazard-mitigation plan-a so-called Section 409 plan. These plans are intended to require States (and local communities) to confront the natural hazards they are subject to and identify programs and policies that can be implemented to reduce those hazards. In theory, FEMA can withhold disaster-assistance funds if the programs and policies contained in the plan have not been implemented. Politically, however, this is quite difficult to do, and FEMA has chosen not to adopt such a stringent approach. Most States required to prepare Section 409 plans have done so. However, FEMA lacks a clear system for monitoring State progress and compliance with Section 409 plans. Furthermore, once a disaster is over, States are relieved of much of the pressure to undertake planning and mitigation activities.

Coastal Barrier Resource Act

CoBRA, enacted by Congress in 1982, represents an attempt to move away from some of the ill effects of Federal subsidies such as flood insurance and disaster assistance. COBRA'S stated objectives are to reduce growth pressures on undeveloped barrier islands; to reduce threats to people and property of disasters and minimize the public expenditures that typically accompany such disasters; and to reduce damage to fish, wildlife, and other sensitive environmental resources.

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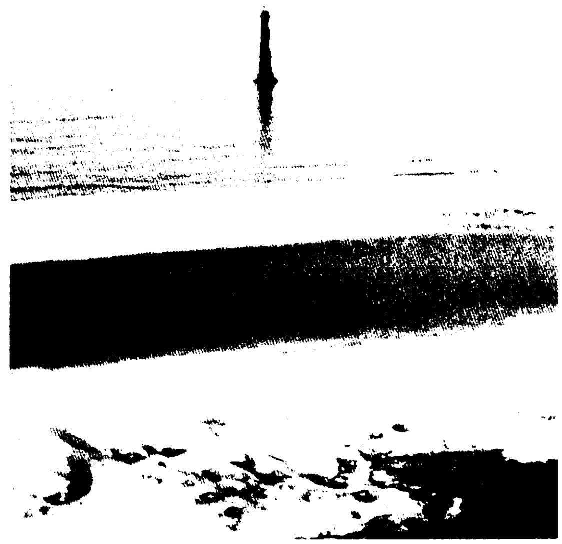


Morris Island lighthouse, once on solid ground, now sits in the Atlantic Ocean off Charleston, South Carolina.

The act designated the Coastal Barrier Resources System (CBRS), originally comprising 186 undeveloped barrier-island units, including 453,000 acres (183,500 hectares)[28] and 666 miles of shoreline. After a certain date, several Federal subsidies would no longer be permitted in these designated areas, including new flood-insurance policies, monies for infrastructure construction, and nonemergency forms of disaster relief. The Department of the Interior is responsible for implementing the program.

Barrier islands were defined in the act as including sand deposits, such as barrier islands and spits, and 'associated aquatic habitats," such as adjacent marshes and estuaries. A barrier island was deemed to be undeveloped, and thus eligible for inclusion in the system, if it had less than one walled and roofed building per 5 acres of land; there was an absence of urban infrastructure on it (e.g., vehicle access, water supply, wastewater disposal, and electrical service to each lot); and

[28] To convert acres to hectares, multiply by 0.405.

it was not part of a development of 100 or more lots (32).

CBRS was expanded in 1990 under the Coastal Barrier Improvement Act (P.L. 101-591) to include 560 units comprising 1.3 million acres and 1200 shoreline miles (88). In addition, under the 1990 act, the Department of the Interior was directed to map all undeveloped coastal barriers along the Pacific Coast (for eventual inclusion by Congress in CBRS).

Several studies have sought to evaluate the effectiveness of CoBRA at discouraging barrier-island development (31, 32,42, 88). These studies suggested that COBRA has not stopped development pressures on undeveloped coastal barriers, although the withdrawal of Federal subsidies has had some effect on discouraging new development there. The General Accounting Office (GAO) noted that the "availability of accessible coastal land is limited [and] populations of coastal areas are expected to increase by tens of millions by the year 2010. This population increase will further spur market demand, providing an incentive for developers, owners, and investors to assume the risks associated with owning and building in these storm-prone areas" (88).

The study results suggest several policy directions, including the acquisition of undeveloped barrier lands despite the high cost of such a strategy.[29] Some studies in the past have argued that despite the high cost of acquisition, the public savings in the long term still justify such purchases (e.g., see ref. 55). One study (42) recommended removal of the remaining forms of Federal subsidy allowable under the current U.S. Tax Code (e.g., casualty-loss deductions); prohibition of all loans made by federally insured banks and lending institutions (originally waived under Section 11 of CoBRA); prohibition of Federal block grants; and prohibition of federally funded projects occurring outside, yet affecting, designated units.

The Coastal Zone Management Act and State Management Programs

The 1972 enactment of the Federal CZMA has served as a major catalyst for improved coastal planning and management. Under Section 305 of the act, the Federal Government-through the Office of Ocean and Coastal Resource Management within NOAA-provides grants for the development of State coastal-management programs. These programs must contain certain elements, and once approved, Section 306 of the act provides funding for State implementation. Funds are provided on a Federal-State cost-share basis. The Federal share was initially as high as 80 percent, but shares are now equal. In addition to the financial incentive for participation, States were also encouraged to participate as a way of exercising some degree of control over Federal actions and projects in their coastal zones. Thus, once a State's plan is approved, subsequent Federal actions must be consistent with it (per Section 307) to the extent practicable.

Although the program is voluntary, participation has been very high. Of the 35 coastal States and Territories eligible for funding, 29 now have federally approved plans (notable exceptions have been Texas and Georgia, but each is now working toward developing a program). Illinois is the only eligible State not developing a program (note that States along the Great Lakes are also considered "coastal"). Moreover, CZMA has clearly served as a major catalyst for the development of more-extensive and more-effective coastal-management programs. Compared with the State-only management frame work that existed before CZMA, there is little doubt that current coastal-development patterns and practices are more protective of sensitive

29 Reference 88 discusses the *fee-simple and less-than-fee-simple approaches.* Fee-simple acquisition involves purchasing full ownership, or the entire ' 'bundle of rights.' Less-than-fee-simple acquisition involves purchasing less than full ownership, or a partial interest in the land, typically the right to build or develop on all or a portion of the land.

coastal resources and have reduced the exposure of people and property to coastal risks (9, 33).

States have considerable freedom under CZMA to craft a coastal program to fit their individual needs and circumstances. It must include certain basic components, however, including identification of the boundaries of the coastal zone, definition of permissible land and water uses within the zone, creation of an inventory and designation of areas of particular concern, and identification of the means by which the State will exert control over activities in the coastal zone. Some States-Florida and New Jersey, for example--have taken a networking approach, pulling together into their coastal programs several already-existing management provisions. Other States, such as North Carolina, have created entirely new management and regulatory frameworks and new State decision-making bodies to implement the program (9).

There is considerable variation in the specific provisions and management tools used in State coastal programs and in their stringency and extent of coverage. Some State programs clearly have made major strides in reducing the riskiness of coastal development. At least 13 States now impose some form of coastal setback, requiring new development to locate a certain distance landward of the ocean (table 4-9) (38, 59,71, 89).

Increasingly, these setback requirements are calculated according to local erosion rates. North Carolina, for example, uses one of the toughest erosion-based setbacks. Specifically, for small-scale development in beachfront areas, new development must be set back a distance of at least 30 times the average annual rate of erosion for that particular stretch of coastline, measured from the first stable line of vegetation (61, 71). Development must also be landward of the crest of the "primary dune" and of the landward toe of the "frontal dune." For larger structures, the setback is doubled to 60 times the annual rate of erosion.

Other types of restrictions are also imposed. Under New York's Coastal Erosion Hazard Areas

Table 4-9--Status of U.S. Setback Authorities

State or Territory	Setback legislation	New policies for sea level rise
Alabama	Yes	No
Alaska	No	No
American Samoa	No	—
California	No	No
Connecticut	No	No
Delaware	Yes	No
Florida	Yes	No
Georgia	No	No
Guam	No	—
Hawaii	Yes	No
Illinois	No	No
Louisiana	No	No
Maine	Yes[a]	Yes
Maryland	No	No
Massachusetts	No	No
Michigan	Yes	No
Minnesota	No	No
Mississippi	No	No
New Hampshire	No	No
New Jersey	Yes[b]	No
New York	Yes	No
North Carolina	Yes	No
Northern Marianas	Yes[a]	—
Ohio	No	No
Oregon	No	No
Pennsylvania	Yes	No
Puerto Rico	Yes[a]	—
Rhode Island	Yes	No
South Carolina	Yes	Yes
Texas	No	No
Virgin Islands	Yes[a]	—
Virginia	No	No
Washington	No	No
Wisconsin	No	No

a State has a construction setback, but It is not primarily for coastal-erosion-hazard purposes.

b The State setback currently applies only to projects requiring a State coastal Area Facility Review Act (CAFRA) permit (i.e., projects of greater than 24 residential units). A proposed bill would revamp CAFRA and give the State greater control over oceanfront areas. Local municipalities have authority for "sub-CAFRA" projects through dune- and beach-protection ordnances.

SOURCES: J. Houlahan, "Comparison of State Coastal Setbacks to Manage Development In Coastal Hazard Areas," *Coastal Management, vol.* 17, 1989; P. Klarin and M. Hershman, "Response of Coastal Zone Management Programs to Sea Level Rise in the United States," Coastal Management, vol. 18, 1990.

Act,[30] for example, in certain erosion zones (i.e., so-called 'structural hazard zones' '), only 'movable' structures are permitted (71). Specific density limitations are imposed by some States in certain high-risk locations. Under North Carolina's program, for instance, development in inlet hazard zones is restricted to structures less than 5,000 square feet (450 square meters)[31] in size, and generally must not exceed a density of more than one unit per 15,000 square feet of developable land (61).

Some coastal States have also imposed significant restrictions on the building of erosion-control structures (e.g., seawalls, revetments, and groins). North Carolina, South Carolina, and Maine have banned the construction of new, permanent shore-hardening structures altogether. Such actions serve in the long run to reduce destruction of beaches, and put property owners on notice that should a beachfront structure become subject to erosion hazards, it will not be permissible to allow the construction of such protective (yet damaging) structures. States like North Carolina have managed to resist recent political challenges to such controls.

Most coastal States have also imposed restrictions on development in tidal, or saltwater, wetlands, and a smaller number apply restrictions to nontidal, or freshwater, wetlands. States typically require a permit before certain activities can take place in wetland areas, and usually include a more expansive list of potentially damaging activities than those regulated under the Federal Section 404 program (see below and vol. 2, ch. 4). Regulated activities typically include discharging dredge material, draining wetlands, cutting trees, and destroying vegetation. These regulations often extend to adjacent buffer areas as well. State wetland standards often incorporate many of the key concepts contained in the EPA-developed Section 404(b) guidelines, including restricting development activities to water-dependent uses and forbidding such activities where practicable alternatives exist.

Most state wetland programs also require mitigation when natural wetlands are destroyed or damaged. Imposed mitigation ratios-the amount of created, restored, or enhanced acreage required for each acre of natural wetland destroyed or damaged--can be two-to-one or greater (77).

Many State coastal programs also seek to manage rebuilding and reconstruction after hurricanes or other major flooding events. Most State programs require development permits for rebuilding substantially damaged structures. Hurricanes and coastal-storm events, while exacting substantial human and economic cost, often represent opportunities to rebuild in ways that minimize exposure to future risks (e.g., through relocation and through elevating structures and setting them further back from the water).

The South Carolina Beachfront Management Act (BMA), originally created in 1988, contained some of the most stringent reconstruction provisions in the country when Hurricane Hugo hit the coast a year later (see box 4-C). In enacting the BMA, the State sought to explicitly implement a long-term shoreline-retreat policy. Under the original act, habitable structures that were found to be "damaged beyond repair' (i.e., damaged by more than $66^2/_3$ percent) could only be rebuilt landward of a no-construction zone (the so-called "dead zone"). All structures rebuilt within a larger 40-year erosion zone were also required to move as far landward as possible (see fig. 4-6). The rebuilding of pools and recreational amenities damaged more than 50 percent was also prevented, and restrictions were placed on rebuilding erosion-control structures if damage was greater than 50 percent. Vertical seawalls could be replaced with sloping barriers, but only under certain conditions (6, 70).

Opposition to the rebuilding restrictions after Hurricane Hugo was intense, especially by beach-

M Article 34, New York Environmental Conservation Law.

31 To convert square feet to square meters, multiply by 0.093.

Box 4-C-South Carolina, Hurricane Hugo, and Coastal Development

No natural event illustrates the vulnerability of coastal areas to erosion, flooding, and wind damage more convincingly than the onslaught of a major hurricane. Hurricane Hugo, which hit the coast of South Carolina in 1989, was an unusually powerful storm. Classified as a category 4 hurricane (see box 4-A), Hugo was one of the most powerful storms ever to strike the East Coast of the United States. The storm surge accompanying Hugo exceeded 20 feet (6 meters)[1] above mean sea level in some locations (84). This high water level, plus strong winds and heavy rains, destroyed coastal real estate and affected farms, forests, and coastal habitats along much of the 181-mile (290-kilometer)[2] South Carolina coastline. Such intense storms are rare, but hurricanes of lower intensity and strong storms are a recurring, year-round phenomenon along the eastern seaboard. Each year, millions of dollars of damage to public and private infrastructure and property occurs along the East Coast as a result of these storms. In addition, significant, though usually less well-publicized, damage occurs to the natural environment.

Each year, as well, population in coastal areas increases more rapidly than population in other parts of the country. As a consequence, the exposure of people and property to coastal hazards is steadily increasing. Development pressures in South Carolina and throughout the Southeast are Intense. Between 1980 and 1990, for example, South Carolina's population increased by 13 percent. In coastal counties, however, population increased by 22 percent, and in the popular Myrtle Beach resort, it increased by over 40 percent (15).

Damage to South Carolina from Hurricane Hugo was extensive and was a result of both the intensity of the storm and the density and type of development in the area it struck. The following catalog of losses caused by Hugo illustrates the variety of ways that human lives and ecosystems can be disrupted and suggests the necessity of implementing strong coastal-zone-management policies and of educating the public about the risks of living in hazardous areas.

Homes and buildings—Hurricane Hugo caused about $7 billion in property damages in North and South Carolina, Puerto Rico, and the Virgin Islands, the four principal areas affected. Charleston County, South Carolina, was one of the hardest hit areas, suffering more than $1.9 billion in damages, about 30 percent of the assessed property value of the area According to the American Red Cross, Hugo destroyed 3,307 single-family homes in the major impact area. An additional 18,171 homes sustained major damage, and 56,580 sustained minor damage. More than 12,600 mobile homes were destroyed, and approximately 18,000 units of multifamily dwellings were either destroyed or damaged (1 9). Despite the large number of homes destroyed, many homeowners rebuilt in the same location. Over 90 percent of homes destroyed in the hard hit and affluent communities of Sullivan's Island and Isle of Palms, for example, were rebuilt in approximately the same place, a pattern that was repeated in many beachfront communities.

Tourism-South Carolina's tourist industry depends heavily on coastal attractions and generates more than $8 billion annually. The tourist industry suffered a major blow from Hurricane Hugo. In the Charleston Metropolitan Area, for example, attendance at local attractions during the 3 months following the storm was down 72 percent compared with attendance during the same period the previous year. Attendance finally returned to normal levels 3 years after the storm.

Forests and the forest Industry-About half the land in South Carolina's coastal counties is devoted to either forestry or agriculture. Over 1.8 million acres (0.7 million hectares)[3] of the State's coastal forests were damaged by wind and waterr. Losses on timberlands caused by Hurricane Hugo amounted to about $1 billion.

1 To convert feet to meters, multiply by 0.305.

2 To convert miles to kilometers, multiply by 1.609

3 To convert acres to hectares, multiply by 0.405.

(Continued on next page)

Box 4-C-South Carolina, Hurricane Hugo, and Coastal Development-(Continued)

Seventy percent of saw timber in Francis Marion National Forest northeast of Charleston was downed, and over 6 billion board feet (12 million cubic meters)[4] of pine and hardwood saw timber were damaged. The amount of dead and downed wood amounted to 3 times the annual harvest in the State, enough to house virtually all the people of West Virginia. The damaged trees are now more susceptible to fire and insect attack.

Agriculture-The agriculture industry suffered over $320 million in damages from salt contamination and high winds. immediately after the hurricane, sodium concentrations on some agricultural lands near the coast were 120 times the average annual concentration, and signs of salt stress can still be found on vegetation in coastal and tidal areas (30). Further inland, vegetables and orchards were heavily damaged by the high winds, and many farm structures also sustained damage.

Seafood industry-Of the 316 commercial fishing vessels licensed in South Carolina, 58 (18 percent) were damaged or destroyed. The total damage to vessels amounted to about $3 million (85).

Tax receipts-The effects of Hurricane Hugo on South Carolina's tax base were mixed. Because a large number of properties were destroyed, short-term reductions in tax collections did occur, but this impact was not severe. The property tax rate and other fees were temporarily increased in some hard-hit areas after the storm to maintain services and compensate for loss of some dwellings from the tax rolls.[5] However, many homes destroyed by Hugo were increased in size when rebuilt, and thus assessed at higher rates than before the storm. About haif of the property loss attributed to Hugo was uninsured, so State income tax collections were negatively affected as a result of income write-offs from casualty losses.

Ironically, because of increased demand on lodging, accommodation tax collections increased following the storm. The area also experienced a significant increase in personal income, in part because of a dramatic increase in coastal construction jobs. By the Spring of 1990, nearly 8,000 construction jobs had been added to the State's economy, more than offsetting the 6,800 jobs temporarily lost in the tourist industry. As a result, income and sales tax collections increased, and the net affect on State tax collections was considered a "wash." One estimate set the impact on State tax collection at only $12 million, a figure too small to conclusively attribute to Hugo (80).

Shoreline impacts and beach renourishment—Extensive shoreline erosion was caused by Hurricane Hugo. Some of the most noticeable effects included the erosion of the primary dune ridge system and the reduction in width and slope of beaches. To repair eroded beaches, the State and several coastal communities spent over $1.5 million on emergency dune scraping, over $7 million for the placement of 1.2 million cubic yards (0.9 million cubic meters)[6] of sand on Grand Strand beaches, and about $1.2 million for sand fencing and revegetation between North Myrtle Beach and Folly Beach (44).

Coastal wetlands—Salt marshes escaped significant damage from Hurricane Hugo. Primary productivity in these coastal marshes was virtually unaffected. The high tide during Hugo's landfall may have spared marshes from potential wave damage. During the months after the storm, some marshes advanced into adjacent forests suffering from salt damage, lending support to the hypothesis that sizable storms are capable of altering the boundaries between salt marshes and upland ecosystems (29).

Marine and coastal wildlife—Immediately after the storm, a reduction of salt and oxygen in coastal waters led to extensive mortality of sea life in some areas. Repopulation of most areas occurred within 2 months after the storm, however, as water quality improved (46). Heavy erosion of nesting areas on barrier islands during the storm affected some bird populations, including brown pelicans and royal terns. Inland, wit h the exception of a few areas

4 To convert board feet to cubic meters, multiply by 0.002.

5 Some taxes are still at the raised levels.

6 To convert cubic yards to cubic meters, multiply by 0.765.

affected by the highest storm surges, heavy wildlife mortality was not noted. Some wildlife in forested areas damaged by Hugo, however, maybe suppressed for **a considerable** period **because** damaged forests will require **decades to recover.** Forest species **likely to be** affected **include** gray squirrels, the **red-cockaded** woodpecker, and some forest songbirds (12). Overall, **except** for coastal forests, the natural environment weathered the storm with little long-term damage.

Personal **losses—During** the first weeks after Hurricane Hugo, some disaster **victims** experienced anxiety and mental disorientation (4). Eight in 10 reported experiencing more than **normal** depression (57). Although these emotional effects of Hugo decreased with time, other personal losses **could** not be restored. These **include items destroyed** in the hurricane that, although **of little intrinsic value,** had great personal significance **to individuals.**

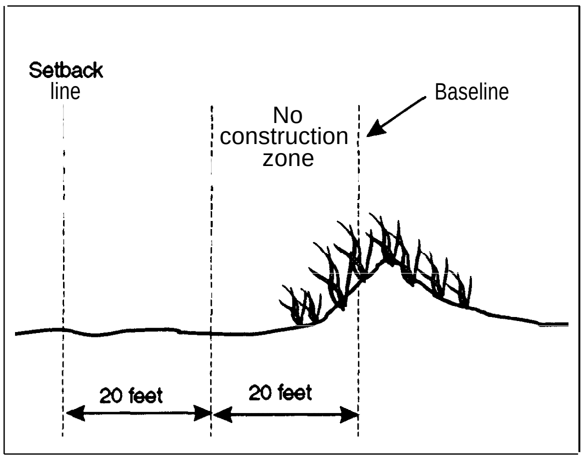
Coastal development **is a double-edged** sword in South **Carolina, as it** is in other States. Living **near the coast** has a strong attraction for many, and as communities grow, **local** revenues increase and public **services improve.** However, as people move to **coastal** areas, they expose themselves not only to **occasional** intense events **like** Hurricane Hugo but to more mundane, but **still** potentially costly, risks such as erosion and sea **level** rise. Hugo-strength storms are rare, but category 2 and 3 hurricanes strike the South Carolina coast about once every 7 or 8 years, on average.

SOURCE: MA. Davidson, Executive Director, South Carolina Sea Grant Consortium, K.H. Duffy, Duffy and Associates, DJ. Smith, Southeast Regional Climate Center, and A. Felts, University of Charleston, personal communication, May 14, 1993.

front-property owners.[32] Moreover, several * ings decisions (e.g., *Lucas v. South Carolina Coastal Council)* suggested that the State's financial liability in cases where the dead-zone restrictions prevented all reasonable use of a parcel could exceed $100 million. In 1990, the South Carolina legislature amended the law, completely eliminating the dead zone and creating a special variance procedure allowing development to occur even further seaward than the dead zone under certain conditions. Despite creating somewhat stronger rebuilding restrictions for erosion-control devices, the 1990 revisions in many ways represent apolitical "retreat from retreat" (6).

Increasingly, State coastal programs are requiring that local governments prepare hurricane and coastal-storm recovery and reconstruction plans. North Carolina was the fiist State to impose such requirements, but other States have followed suit (e.g., Florida and South Carolina) (34). Some States have begun to explicitly incorporate consideration of sea level rise into their programs. Seventeen coastal States have officially recognized the problem of sea level rise and have undertaken assessments of the issue (45). Eleven of these have initiated new public and intergovernmental processes (e.g., forming a sea level rise task force), and 13 States have existing regulations that are adaptable (or partially adaptable) to

Figure 4-8-New **Zones** Established by Beachfront Legislation



SOURCE: T. Beatley, "Risk Allocation Policy in the Coastal Zone: The Current Framework and Future Directions," contractor report prepared for the Office of Technology Assessment, February 1993. . .

32 Some 159 beachfront structures located in the no-construction zone were found to be damaged beyond repair by Hugo.

Box 4-D-The "Maine Approach"

One response to sea level rise that may allow room for wetlands to migrate (see vol. 2, ch. 4), as well as maximize the human use of the coastal zone at minimum cost, has been implemented by the State of Maine. This State has adopted a **policy** of allowing development in the coastal zone to continue subject to the constraint that structures will have to be abandoned if and when sea level rises enough to t **hreaten** them (52). Ail new structures, therefore are presumed movable. This so-called "Maine approach" will likely be less expensive than preventing development because coastal land would remain in use until the sea rises a given amount, whereas restricting development prevents the property from being used in the interim even though its inundation maybe decades away. The presumption of **movability** is more **flexible** than restricting development because it does not require a specific estimate of how fast the sea will rise or the shore will **retreat,** or how far into the future one should plan. It also **enables** private real estate markets to discount iand **prices** according to information on the risk of sea **level** rise.

The Maine approach can be implemented in several ways. Maine has explicitly adopted this policy along its sand dune and **wetland** shores, with regulations that: 1) prohibit bulkhead construction, 2) explicitly put property owners on notice that structures are presumed to be movable, and 3) require property owners to affirmatively demonstrate their intention **to abandon the** property before being granted a permit to erect a structure in any area that would support wetland vegetation if sea level rises 3 feet (0.9 meters). Although implemented in 1989, the Maine approach has not yet been tested, so it is uncertain how **well** the approach will work if sea level rise actually becomes a problem. States' abilities to require or induce private property owners to allow coastal **wetlands** to migrate with arising sea **will** hinge on the **balance** between t he rights of private property owners and public trust doctrines. if the Federal Government wishes to promote this type of adaptation, it might do so through changes in the Coastal Zone Management Act (P.L. 92-583) when it is reauthorized in 1995.

several other **States—including** North **Carolina—have implicitly** adopted the Maine approach along the ocean coast by prohibiting the construction of sea **walls** while continuing to allow construction of bulkheads along **wetland** shores. In some States, a strict interpretation of the common iaw **"public** trust doctrine" **would** hold that as the shoreline migrates inland, so do the public rights to use tidelands for access and environmental purposes, **including** wetlands. Finally, private conservancies can implement this approach by purchasing coastal **lands** and then **reselling** them at a slight discount in return for deed restrictions prohibiting bulkheads or requiring that the property revert to the conservancy whenever the sea reaches a threshold.

SOURCE: **Office of Technology Assessment, 1993.**

future sea level rise (e.g., coastal setbacks, such as those discussed above). Only three, however, have adopted new policies specifically to respond to sea level rise (45).

Under Maine's Natural Resources Protection Act, wetland buffer zones are established to anticipate migration in response to sea level rise. As this zone moves in the future, development within it must also move (specifically, development must be relocated or abandoned if water encroaches on the development for more than a 6-month period or if it is damaged 50 percent or **more)(45)** (see box 4-D). Also, in certain **frontal-**dune areas (where some development is permitted), developers are required to build structures exceeding a certain minimum size to take into account a predicted 3-foot rise in sea levels over the next 100 years (45).

Some State programs have sought to facilitate and promote landward relocation of structures. In response to rising Great Lake levels, the State of Michigan created the Emergency Home Moving Program **(EHMP).** Under this emergency program, the State provided loan-interest subsidies to property owners wishing to relocate lakefront structures threatened by erosion (71, 76). Property owners had a choice of either a 3 percent interest subsidy on the frost $25,000 of relocation costs or a one-time grant of $3,500. As a condition of this assistance, property owners had to move their structures at least 45 feet landward. The State also implemented an Emergency Home Flood Protection Program, which provided similar subsidies for the elevation of threatened structures (71).

Another strategy some States are using is the acquisition of coastal-hazard areas and sensitive lands. State programs, such as Florida's Preservation 2000 program and California's Coastal Conservancy program, have been very effective at protecting wetlands, beaches, and other sensitive coastal lands through outright purchases.[33]

Many State coastal programs also impose some form of real estate disclosure requirement, which may be useful in discouraging hazardous development. Under North Carolina's program, for example, an applicant must sign an Areas of Environmental Concern Hazard Notice to acknowledge that "he or she is aware of the risks associated with development in the ocean-hazard area and of the area's limited suitability for permanent structures" (61). Under South Carolina's modified beachfront-management program, similar disclosure provisions are required when a special beachfront variance is issued (6).

Building codes and construction standards represent another important component of many State and local risk-reduction strategies (although not necessarily an explicit component of a State's coastal program). Coastal structures can be designed to better withstand hurricane winds, waves, and storm surges. Building codes may be State-mandated (as in North Carolina) or locally mandated (as in South Carolina) and can vary substantially in stringency. The Federal CZMA does not mandate that States impose building codes, and, in some 12 coastal States, adoption of building codes is left as a local option. It is not uncommon for rural areas especially to have no construction standards (53).

The stringency of the wind-design standard to which coastal structures must be built is one variable in State programs. Under the N.C. Building Code, for instance, construction on the Outer Banks must be designed to withstand wind speeds of 120 miles per hour (mph). Structures there must also adhere to fairly stringent piling and foundation standards (34). The benefits of North Carolina's standards are illustrated by comparing damages from Hurricanes Alicia and Diana in Texas and North Carolina, respectively (75). Though the storms were comparable in strength and wind speeds, resulting damages were much less in North Carolina. The lower damages appear to be due in part to North Carolina's mandatory construction standards and to the lack of any control over building in unincorporated areas of Texas (see ref. 58).

The South Florida Building Code (SFBC) is considered one of the strongest prescriptive codes anywhere and similarly mandates a 120-mph wind-speed standard. However, inspections of damage from Hurricane Andrew identified several potential deficiencies in the code, including poor performance of roof coverings, poor connection between the roof system and the building, inadequate use of staples to attach plywood sheathing, and problems with windows and wall siding (65). Local enforcement and builder-compliance problems were also identified. Although a relatively strong code, some have argued for even tougher standards given the location, frequency, and potential magnitude of future storm events; density of development; and consequent greater threat that projectiles torn from one home will hit other homes. Others argue that tougher enforcement, not stronger standards, is needed.

33 Preservation 2000 is a 10-year program established in 1990 with the intent of acquiring $3 billion of environmentally sensitive lands over 10 years.

The Federal CZMA, then, has stimulated considerable coastal planning and management that may not otherwise have occurred or would have occurred more slowly. Participation has been high, and even the two nonparticipating oceanfront States, Texas and Georgia, have been developing programs (Section 305 funds are now available again under the 1990 reauthorization of CZMA).

CZMA has suffered from certain implementation problems, however. First, funding levels have not changed much since the early 1980s, with annual implementation monies (Section 306) staying at about $33 million (89). Given the magnitude of the management tasks, individual State allocations seem modest. Provision of additional CZMA monies to States specifically for the development, strengthening, and enforcement of strong shorefront and hazard-area-management provisions could return benefits many fold. Second, the Federal coastal-management program has also historically suffered from a lack of clear and uniform performance standards. Some States have aggressively managed and controlled coastal development whereas others have done little. Third, NOAA has not applied sanctions to States that do not implement their adopted and approved programs. Although programs can be "disapproved," this action has never been taken. (On the other hand, the 1990 CZMA amendments now provide for "interim sanctions" if a State is not performing adequately.)

POLICY OPTIONS FOR THE FEDERAL GOVERNMENT

Although some important improvements in managing coastal development have been made in recent years, additional improvements are likely to be needed to forestall unwise development and to decrease existing vulnerability. The potential for sea level rise and more frequent and/or intense storms as a result of climate change adds to the already significant vulnerability of both developed and natural areas in the coastal zone. The following options for readjusting the existing incentive structure in coastal areas should be viewed as a starting point for additional discussion about appropriate changes. These possible changes are summarized in table 4-10.

Revamping the National Flood Insurance Program

The NFIP still provides subsidies to a substantial number of buildings in high-risk coastal areas. Current NFIP policy has been established by Congress, and Congress could make program and policy changes to the NFIP to reduce these subsidies and otherwise improve flood-mitigation activities and reduce damages from coastal hazards. Several bills suggesting such changes have been introduced into the 103d Congress, including S. 1405, the National Flood Insurance Reform Act of 1993, and H.R. 62, the National Flood Insurance, Compliance, Mitigation, and Erosion Management Act of 1993. Several options discussed below could be incorporated into these bills as they evolve.

Option 4-1: *Raise premium rates for the policyholders who receive subsidized flood insurance.* Despite the gradual increase in rates over the years, the average yearly premium paid by coastal property owners remains modest relative to the risk. The potential for catastrophic future storms and sea level rise associated with climate change suggests that the risks of living near the coast will be greater in the future. If the availability of flood insurance is to be maintained, rates may need to be raised to reflect these factors. Currently, rates reflect only average annual losses; occasional catastrophic losses can be much higher than average. Rates might be raised to incorporate an 'increased cost of reconstruction' benefit into policies.

Option 4-2: *Mandate erosion-management standards.* The current NFIP does not adequately address long-term erosion trends. One way it could do so would be to require minimum erosion-management standards. For example,

Table 4-10--Federal Programs and Laws Influencing Coastal Development: Status and Potential Changes

Federal program	Key provisions	Legislative basis	Existing mitigation provisions	Potential changes and policy options
National Flood Insurance Program (NFIP)	Provides Federal flood insurance to property owners in participating communities Communities must adopt minimum floodplain management provisions (e g., elevation to 100-year-flood level, restrictions to building in floodway	National Flood Insurance Act Flood Disaster Protection Act	Minimum floodplain-management standards, Upton-Jones relocation assistance Community Rating System 1362 flooded properties purchase program	Adjust premium rates Mandate erosion-management standards. Curtail insurance for high-risk, repetitive-loss properties, Prohibit new insurance in risky locations. Incorporate sea level rise in mapping and rate structure Expand relocation assistance
Disaster assistance	Individual and family grants program Public-assistance grants on 75-25 cost share	Stafford Disaster Relief and Emergency Assistance Act	Mitigation grants program Section 409 State mitigation plan required.	Reduce Federal share for public assistance Require more stringent mitigation Impose ability-to-pay standard Eliminate public-assistance funds altogether, Review criteria for declaring disasters.
Coastal-barrier management	Withdraws Federal subsidies for new development in designated Coastal Barrier Resources System (C BRS); prohibits issuance of new flood insurance, post-disaster assistance, and other development funds,	Coastal Barrier Resources Act (COBRA)		Further limit subsidies. Expand coverage to other sensitive lands. Promote State coastal barrier resource acts. Acquire undeveloped areas
Federal tax benefits	Casualty-loss deduction, Interest and propertytax deductions for second homes. Accelerated depreciation for seasonal rental properties.	U S Tax Code		Eliminate or reduce tax benefits for coastal development Create tax deductions to support mitigation.
Coastal zone management	Federal funds and technical assistance for developing and implementing State coastal-management plans (cost-share basis).	Coastal Zone Management Act (CZMA)	State coastal-management plans (e.g., ocean-front setbacks, land acquisition, construction standards, post-storm reconstruction standards).	Mandate stronger development controls. Expand resources available to coastal States.

Table 4-10--Federal Programs and Laws Influencing Coastal Development: Status and Potential Changes--(Continued)

Federal program	Key provisions	Legislative basis	Existing mitigation provisions	Potential changes and policy options
Beach renourishment and shore protection	Provision of funding and technical assistance for beach-renourishment and shore-protection projects. Federal cost share from 55 to 90 percent	Federal Flood Control Acts (of 1917, 1936, 1945, 1955, 1968; for a detailed review of these, see ref. 71)		Discourage permanent shoreline stabilization. Increase State and local contribution. Phase out Federal funding of beach renourishment. Condition funding on minimum State and local coastal management.
Federal wetland protection	Restricts discharge of dredge and fill materials into U.S. waters.	Section 404 of the Clean Water Act	Section 404 (b)(l) guidelines, and U.S. Army Corps of Engineers public-interest review.	Tighten regulatory control in Section 404 permit review, Incorporate sea level rise into wetland management decisions. Explore use of transferable development rights.

SOURCE Office of Technology Assessment, 1993

minimum **State** or **local erosion setbacks could be required as a condition of participation in the NFIP (see also option 4.18, below). Alternatively, communities could be penalized for failure to adopt minimum setbacks-for example, by making them ineligible for mitigation and relocation assistance, by raising insurance premiums,** or by **reducing future claims in 10-year** erosion zones. Erosion-based setbacks, such as these in North Carolina, represent models, although the time frames used for calculating the setback could be expanded. Where lot depths or project designs allow, more extensive setbacks could be encouraged or required, for example. Another option for addressing erosion would be to factor long-term erosion trends into the premium rate structure for existing and future policyholders.

A precursor for improved erosion management is identifying and mapping erosion risks. Property owners are not anxious to have such risks identified due to potential adverse effects on **housing** values, **but** construction in erosion zones is risky and potentially costly to the Federal Government as well as to both present and future property owners. The Federa1 Insurance Administration is currently working, on guidelines and **standards for mapping erosion zones, but Congress needs to give the agency the authority to begin mapping.**

Option 4-3: *Prohibit new insurance policies in risky locations. NFIP* **could take several actions to reduce** its **long-term insurance liability and to bring the program more in line with the risk-averse philosophy of private-sector insurers. It could acknowledge that development in certain locations** is **extremely risky and prohibit all new insurance policies in these locations. In particular, the program could be changed so that no new insurance would be issued in V zones or in high-risk** erosion zones (e.g., within a 10-year erosion zone). H.R. 1236, introduced in the 102d Congress, contained language prohibiting all new flood-insurance policies for development seaward of the 30-year erosion line. Eventually eliminating new insurance within the 50-year erosion zone might also be considered.

A downside of this option is that it would limit the number of people paying into the fund. Also, those who insisted on building without flood insurance might still be helped by disaster relief after a major disaster but would have contributed nothing in the way of insurance premiums.

Option 4-4: *Increase insurance premiums after each claim on properties subject to multiple-flooding claims.* Current NFIP regulations do not substantially restrict how often a homeowner may rebuild after a loss, even if a future loss can be reasonably foreseen. By tying insurance premiums in high-risk areas to the number of losses a property has sustained, homeowners will have more incentive to consider coastal hazards in rebuilding decisions. Congress could also consider establishing a limit on the number of claims permissible before insurance is terminated (e.g., just as an automobile-insurance company might terminate a policy in the event of multiple accidents).

Option 4-5: *Incorporate sea level rise into the NFIP mapping and rate structure.* As discussed in earlier sections, future sea level rise may serve to substantially increase the size of the coastal zone subject to inundation and flooding in the future. The current NFIP mapping and rate structure does not take this into account, in part because FEMA contends that a 12-inch rise in sea level would not significantly affect the ability of the rating system to respond (21). Incorporation of even conservative estimates of sea level rise into FEMA maps might serve to discourage future development in these areas and put coastal communities and property owners on notice about such future risks. Development that does occur in these areas would be subject to certain minimum flood-management standards (e.g., elevation requirements). A means of accomplishing essentially the same goal may be to update floodplain maps more frequently. More-frequent updates would reflect changes related to sea level rise as well as those related to recent development. FIA maps are currently updated, on average, only once every 9 years. FIA's own goal for revisions is once every 5 years. More frequent updates would require more staff and additional funds.

Option 4-6: *Expand relocation assistance. FEMA* and NFIP could substantially expand the emphasis given to relocation assistance. The existing Section 1362 and Upton-Jones programs represent good strategies but are underused and underfunded. Section 1362, or something like it, could be expanded and funding could be increased. Efforts could be made to expand the use of Upton-Jones, as well, and to promote relocation as an alternative over demolition. Among possible improvements to Upton-Jones that could be considered are: 1) requiring relocation outside high-risk locations (e.g., landward of the 30-year erosion line), not simply making future insurance conditional on such relocation, and 2) expanding eligibility beyond the currently narrow definition of imminent collapse.

Incentives to relocate could be made stronger by modifying the ways in which NFIP treats structures that are at risk because of erosion. Requiring higher premiums for structures seaward of certain erosion zones (e.g., the 30-year erosion line) would create financial incentives to relocate. Cutting off insurance to structures within a zone of imminent collapse (e.g., within the 10- or 5-year erosion line) after a certain period of time (e.g., 2 years after a chosen date) may have a similar effect, but property owners whose homes were subsequently destroyed could still claim casualty-loss deductions, thus offsetting other Federal tax liabilities.

The Federal Government may also wish to help States develop their own more-extensive relocation-assistance programs. Just as the Federal Government has helped States establish revolving funds to finance improvements in local sewage-treatment plants (see ch. 5), so also could the Federal Government help States establish coastal-relocation revolving funds.

Under the Clean Water Act P.L. 92-500), the Federal Government has encouraged creation of State wastewater revolving funds through the provision of start-up capitalization grants. Once established, States then allow local governments to borrow funds for the construction of new wastewater treatment facilities or the improvement and upgrading of existing facilities. Loans are provided at interest rates at or below fair market (depending on factors such as a community's financial circumstances and the severity of the water-quality problem). In the case of Virginia's Water Facilities Loan Fund, annual payments back to the fund are required, and full repayment of loans must occur within 20 years (e.g., see ref. 92). Thus, annual repayment by borrowers ensures a steady pool of funds available for new loans.

Such revolving funds could be similarly useful in providing grants to assist private property owners in locating and purchasing alternative coastal or noncoastal sites. State revolving funds might be used to purchase relocation sites in advance, later making them available to beachfront-property owners needing to relocate. Property owners could then be asked to repay the fund for these acquisition costs, perhaps at below-market rates.

Such a fund could also be useful in purchasing damaged properties after a hurricane or major storm event, in turn selling or relinquishing these lands to local governments for needed beach-access points and public recreational areas. In rare cases, land swaps may be possible, allowing a beachfront-property owner to trade for a State-acquired relocation lot further inland.

States could also be required to consider and incorporate relocation strategies and programs in the hazard-mitigation plans required by Section 409 of the Stafford Act (71). Relocation programs could be a minimum-requirement component of State 409 plans.

Revamping Disaster Assistance

The existing disaster-assistance framework could be modified in several ways to reduce incentives for hazardous and costly coastal development patterns, including the following.

option 4-7: *Reduce the Federal share of public assistance.* Typically, the Federal Government share of disaster-assistance funds for States and communities has been 75 percent. In some recent cases, the Federal Government has provided 100 percent of the disaster-assistance monies. Although it is difficult to specify what the Federal share of such assistance ought to be, very high levels of assistance are probably a disincentive to improving State and local disaster mitigation. Unsuccessful efforts have been made in the past to reduce the Federal share to no more than 50 percent. Cost-sharing proportions have changed in other areas, however. For example, the Federal share of water-resources-development studies has been reduced from 100 to 50 percent in recent years in a successful effort to motivate more thoughtful State consideration of water projects (see ch. 5).

Option 4-8: *Tie disaster assistance more strongly to State and local hazard-reduction programs.* The mitigation provisions and requirements currently included under the Stafford Act are already strong. However, a shortcoming may be that FEMA does not force States and localities to adopt mitigation (e.g., a dune-protection ordinance) as a condition of disaster assistance. FEMA rarely withholds disaster-assistance funds from States that fail to adopt or implement mitigation measures. Most States prepare Section 409 mitigation plans, but there is generally no mechanism for requiring or ensuring that States implement the plans. Thus, FEMA could adopt a more stringent view of mitigation, more clearly and aggressively tying disaster-assistance funds to tangible, long-term hazard-reduction policies, programs, and actions.

It may also be useful to establish some clearer system for judging State accountability for Section 409 progress. States could be required to more clearly indicate the mitigation actions they agree to adopt and implement within a specified time frame (e.g., adopting a shoreline setback requirement). Although politically difficult in the face of a disaster, the Federal Government could specify that subsequent Federal disaster assistance would not be provided where the plan has not been implemented. Alternatively, subsequent assistance could be limited, for example, to no more than 50 percent of otherwise eligible funding, or States could be required to repay disaster assistance if mitigation measures are not adopted within a specified period.

FEMA could try to establish a system for certifying that State 409 plans meet a minimum mitigation threshold, that is, that they contain actions and policies sufficient to bring about a substantial degree of long-term risk reduction. For example, coastal States could be required to adopt a building code (or mandate local adoption) and to ensure that an adequate system of implementation and enforcement will exist. Such minimum construction standards (perhaps one of several standard codes) could be made a condition of participation in the NFIP, or of receiving funding under CZMA. The Federal Government could also consider raising national wind standards for mobile homes.

Option 4-9: *Consider ability to pay and extent of damages. The existing* disaster-assistance framework fails to explicitly consider the ability of affected localities and States to assume disaster losses, or the extent of damage actually incurred. Once a disaster area is designated, all localities are eligible for disaster assistance regardless of the extent or size of damage incurred. Much Federal disaster assistance is provided in small amounts to numerous localities--damage levels that could clearly be covered by local governments. Furthermore, certain localities (and States) are wealthier and have a greater capacity to pay for and assume the costs of hurricanes and other disasters. FEMA has proposed a $2.50 per capita threshold for costs per disaster to determine when local resources are adequate and when Federal funds are not necessary or appropriate. Survey data indicate that most local governments could easily cope with this level of loss and that a sizable proportion of governments could cope locally with per capita losses of $14 or more (11). A threshold provision would act as a kind of disaster "deductible," and Federal resources would kick in only after it is reached. Such a system would further contribute to greater accountability of local and State governments for their decisions and to greater equity in the disaster-assistance system overall.

Option 4-10: *Eliminate public-assistance funds.* Although not very feasible politically, certain categories of disaster assistance could be eliminated. Although the public generally supports the role of the Federal Government in assisting individuals and families in recovery and rebuilding, this "helping" sentiment may not be as strong when it comes to helping States and localities rebuild boardwalks or local streets. One possibility would be to develop alternatives to outright grants, including creating a Federal public-assistance-loan program. If local governments need to borrow funds to rebuild sewer systems, roads, and recreational amenities, this kind of program would make such funds available but subject to repayment with interest. Loans could be offered at below-market interest rates. Such an arrangement may result in more cautious local and State investment policies. Another possibility might be to develop some type of insurance fund for local governments.

Option 4-11: *Through oversight hearings, Congress could review the criteria used by the President to declare disasters. One* question that could be investigated is whether existing criteria are too generous in situations that are not major disasters.

Extending and Expanding the Coastal Barrier Resources Act (COBRA)

Although withdrawal of Federal subsidies from barrier-island development clearly will not stop such development, it has been shown to slow it. Moreover, this approach is sensible from the perspective of taxpayer equity: if developers and coastal property owners choose to build in high-risk locations, at least the general public would not have to pay for it. The COBRA experience is positive, but efforts could be made to expand its coverage and strengthen its provisions.

option 4-12: *Further limit subsidies.* As noted earlier, COBRA does not eliminate all Federal subsidies. Important remaining subsidies include the casualty-loss deduction under the U.S. Tax Code, Federal block grants., and grants and loans from federally insured banks. COBRA could be strengthened, and coastal development on designated units further discouraged, by eliminating these remaining subsidies. CoBRA could also be modified to prohibit Federal subsidy of projects and expenditures that, although technically outside the Coastal Barrier Resources System, serve to directly encourage or facilitate development (e.g., construction of a bridge).

Option 4-13: *Expand coverage to other sensitive lands.* Consideration should also be given to expanding the kinds of lands to which Federal subsidies are limited, including other sensitive coastal areas besides barrier islands. These could include coastal wetlands (and wetland buffer zones), estuarine shorelines, critical wildlife habitat, and Other areas (see vol. 2, ch. 4). Substantial resource-management benefits could result from the "CoBRA-cizing" of other sensitive lands. Also, efforts to expand the CBRS to the Pacific Coast, although currently meeting some resistance, could be continued.

Option 4-14: *Encourage the development of State COBRAS.* Florida is one State that has imposed certain limitations on future State investments in high-risk coastal areas, but few other States have such restrictions. One way the Federal Government could encourage development of CoBRAS in other States and reinforce the effects of Federal limitations is to require as an element of State coastal-zone-management plans that States consider the circumstances under which restrictions on State investments in coastal areas might be appropriate. Restrictions on expenditures for State roads and bridges might be considered, for example. This change could be implemented when CZMA is reauthorized in 1995.

Option 4-15: *Acquire undeveloped areas.* Although COBRA has been able to slow development of barrier islands, studies by the U.S. General Accounting Office and others illustrate that development will likely continue in many places despite withdrawal of Federal subsidies (88). Consequently, consideration should be given, as suggested by GAO and others, to acquiring many of the remaining undeveloped barrier-island units.

Acquisition now, though costly, may be cost-effective in the long run. Acquisition is especially warranted for barrier-island units of special ecological importance (e.g., those that contain endangered species habitat) and in areas that could provide important public-recreation benefits. Acquisition could be encouraged at Federal, State, and local levels, and in concert with private conservation groups and land trusts. At the Federal level, the U.S. Fish and Wildlife Service is the logical agency to spearhead such acquisition (see also vol. 2, chs. 4 and 5).

Revamping the U.S. Tax Code

As discussed in earlier sections, the U.S. Tax Code offers several major subsidies for coastal development, including casualty-loss deductions for damage from hurricanes and storms, depreciation tax shelters for seasonal rental properties, and deductibility of mortgage interest and property taxes for second homes. The actual effect of these tax benefits is difficult to determine. They do represent another major category of public subsidy of coastal development.

Option 4-16: *Eliminate or reduce tax benefits for coastal development.* For example, the casualty-loss deduction (that is, the deduction for losses in excess of insurance coverage) could be eliminated altogether for risks peculiar to the coastal zone, or restricted only to damages that occur to a principal residence (see ref. 71).

Option 4-17: *Modify the Tax Code to support and encourage mitigation. This* could be accomplished, for instance, by providing a tax deduction for home improvements intended to mitigate storm damages or for expenses associated with relocation (including purchase of a relocation lot).

Strengthening State and Local Coastal Management

Generally, coastal States and localities are in the best position to manage and control coastal development. Also, efforts to impose land-use planning or land-use controls at the Federal level have met with great skepticism and political opposition at the State level. On the other hand, the Federal CZMA has been successful in motivating improvements in coastal planning and management since it was passed more than two decades ago. Significantly, the 1990 amendments to the CZMA recognized for the first time the potential importance of climate change and sea level rise and called for coastal States *to* anticipate and plan for these possibilities. CZMA could be further modified and reinforced, when reauthorized in 1995, to promote greater risk reduction and more sensible land-development patterns.

Option 4-18: *Mandate certain specific--and stronger+ minimum development controls. These* could include, for instance, an erosion-setback program (already adopted by several States), restrictions on construction of immovable buildings, a relocation-assistance program and restrictions on rebuilding damaged or destroyed structures in high-risk locations, and adoption of minimum coastal-construction standards. Major Federal financial subsidies could be accompanied by the adoption of certain minimum risk-reduction measures. Minimum measures could also include wetland protection (possibly including protection of buffer and migration areas-see vol. 2, ch. 4) and minimum consideration of sea level rise in coastal programs.

The CZMA program could also be adjusted to create financial incentives to undertake additional risk-reduction measures. The current coastal-zone-enhancement grants program (Section 309) represents a movement in this direction and does include, as areas eligible for funding, management and protection of coastal wetlands and management of natural hazards (including sea level rise). More comprehensively, a "coastal-hazards-management program' could be required as a component of State CZM programs. Such a program might be modeled after the non-point-source-pollution-management program that participating coastal States were required to develop under the 1990 CZMA amendments. EPA and NOAA together oversee this program and jointly approve the State programs. A similar arrangement could be created with NOAA and FEMA.

Option 4-19: *Expand available resources. The* current level of funding provided to coastal States is meager at best. Annual appropriations for State program implementation (Section 306 funds) have remained around $33 million, despite the fact that the magnitude of coastal-management problems is increasing. Also, since the number of States participating in the CZM program has increased, funding available per State has decreased. Adequate funding is needed to implement State regulatory and development provisions (e.g., setback requirements) and to facilitate local coastal planning. Additional funding earmarked for State actions and programs that reduce coastal risks could also be provided. Funding for such coastal-planning activities could be a cost-effective expenditure that can serve to reduce long-term risks, as well as to better protect coastal environmental resources.

The Federal Government could also, to the extent possible, help to facilitate the development and implementation of State land-acquisition programs. Programs such as Florida's Conservation and Recreation Lands (CARL) program and California's Coastal Conservancy represent some of the most effective and sensible strategies for protecting wetlands, barriers, and other sensitive coastal lands and for preventing future exposure of people and property to coastal risks. The Federal Government could facilitate such programs by providing technical assistance and seed monies for State acquisition funds.

Shoreline Protection and Beach-Nourishment Programs

Significant subsidies to coastal development have also occurred through the programs and activities of the U.S. Army Corps of Engineers, including construction of shoreline-stabilization structures and funding of beach-nourishment projects.

Option 4-20: *Discourage permanent shoreline stabilization where feasible.* Several States have taken the lead in banning permanent shore-hardening structures such as sea walls and groins. Such Projects are costly and may actually increase development pressures. The Corps (or Congress) could develop a long-term coastal-management strategy that explicitly discourages the use of such hard shoreline techniques, except where absolutely necessary. Priority could be given to beach renourishment and approaches that are less environmentally damaging.

Option 4-21: *Increase State and local contributions and phase out Federal finding of beach-renourishment projects.* Concurrently, States could be encouraged to ensure that a substantial portion of renourishment costs are borne by beach-front communities and property owners. Ideally, the property owners and businesses directly benefiting from these investments would bear the lion's share of their costs. Renourishment can legitimately be considered a maintenance cost and, therefore, not eligible for Federal funding. Earmarking local revenue sources, such as special tax (renourishment) districts, a dedicated sales tax, or a tourist tax, could be encouraged.

As an alternative, Federal funding could be eliminated entirely (or phased out over time), and perhaps replaced with Federal seed monies for States to establish revolving-fund renourishment programs. An approach could be taken similar to that used for Federal funding of sewage treatment plants under the Clean Water Act (see ch. 5).

Option 4-22: *Make the Federal proportion of funding for renourishment projects conditional on adoption of certain State and local coastal-management initiatives. These* could include, for example, setback requirements, post-disaster restrictions, and relocation assistance.

Strengthening Wetland Protection

The Federal Government currently exercises substantial regulatory and management control over coastal wetlands. The existing programs, principally Section 404 of the Clean Water Act, jointly implemented by the Army Corps of Engineers and EPA, could be further strengthened to take into account future sea level rise and to better guard against destruction by coastal-development pressures. OTA'S options for improving wetland protection are discussed m volume 2, chapter 4.

FIRST STEPS

With or without climate change, average annual property damage in the coastal zone is expected to continue increasing (78). People will continue to move into and develop hazard-prone areas. As previously noted, for example, the damage-causing potential of hurricanes is much greater now in many coastal areas than it was several decades ago. This greater threat is attributable mostly to the fact that the coastal zone has become more intensively developed. Moreover, this development trend shows no sign of abating. Thus, coastal hazards are not just the result of uncontrollable natural phenomena. Rather, the growing coastal population both contributes to and modifies such hazards.

We suggest in this chapter that improvements can be made in allocating and managing risk in coastal areas. However, given current demographic trends, the longer the Nation waits to address the shortcomings of current policies, the more difficult and expensive coping with future disasters will be. There is no need to wait for unequivocal information about the nature of climate change; acting now to mitigate coastal hazards through implementation of prudent policies is likely to save both the public and private sectors substantial sums in the coming decades, as well as save lives and natural areas and improve the quality of coastal living. When climate change is considered, however, with its potential for accelerated sea level rise and the possibility of more-intense or more-frequent storms, the case for strengthening existing policies is even more compelling.

Implementation of some or all of the options considered in this chapter could help send clearer signals to residents, potential residents, businesses, and visitors of coastal areas about the nature of coastal risks and the costs associated with those risks. Many of the options suggested in this chapter would also promote the flexibility and efficiency needed for adapting to a changing climate. Several bills now before the 103d Congress and some upcoming reauthorizations of existing laws could provide excellent "targets of opportunity" for implementing some of these options.

- Revamp the National Flood Insurance Program. Congress has been considering revamping the National Flood Insurance Program for several years, and bills to do this have been introduced in both the House and Senate. S. 1405, the National Flood Insurance Reform Act of 1993, and H.R. 62, the National Flood Insurance Compliance, Mitigation, and Erosion Management Act of 1993, contain provisions that partially address some of the NFIP options presented in this chapter (e.g., erosion management, relocation assistance, repetitive losses, and insurance for risky locations). As these bills evolve, other options in this chapter could be incorporated.
- Improve disaster assistance. Several bills have also been introduced in the 103d Congress to revise disaster-assistance policies and regulations. OTA'S disaster-assistance options could be incorporated into these evolving bills. H.R. 935, the Earthquake, Volcanic Eruption, and Hurricane Hazards Insurance Act of 1993, for example, would establish minimum criteria for reducing losses, recommends such measures as fiscal incentives to reduce losses, provides for low-interest loans or grants to retrofit facilities vulnerable to hurricanes, and provides guidelines for establishing actuarial premium rates for disaster insurance. S. 995, the Federal Disaster Preparedness and Response Act of 1993, would establish, among other things, a grant program and accompanying performance standards to help States prepare for, respond to, and recover from major disasters.
- Strengthen coastal zone management. The Coastal Zone Management Act will be up for reauthorization in 1995. OTA's coastal-zone-management options could be included in reauthorization legislation at that time. In particular, mandating that States adopt cost-effective risk-reduction measures as part of their CZM programs would help reduce future vulnerability to climate change. Also, the reauthorization process would be an appropriate time to consider whether a coastal-hazards-management program should be required as a component of State CZM programs. With oversight by NOAA and FEMA, such a program could help improve coordination among government agencies as well as help reduce the risk of living in the coastal zone.
- Promote public education. The public generally is not well-informed about the risks associated with living in coastal areas, and this lack of awareness has led and will lead to large and unnecessary public and private expenditures. Timely public education about erosion, sea level rise, flooding risks, and building codes, for example, could be a cost-effective means of reducing future risk as well as future expenditures. This "first step" does not appear in any of the options presented earlier in this chapter; however, education is equal in importance to all of the programs discussed here. H.R. 935,

the Earthquake, Volcanic Eruption, and Hurricane Hazards Insurance Act of 1993, provides one possibility for expanding public education. The act authorizes education programs and provides States the funds with which to implement them through the establishment of a self-sustaining mitigation fired (Section 104). The private sector, and in particular, the private insurance industry, could also play an important role in increasing awareness of coastal hazards.

- **Require increased State and local contributions to beach-nourishment operations.** Most benefits of the Army Corps of Engineers' beach-nourishment and shoreline-protection projects are realized at the local or regional level, yet these projects are often heavily subsidized. In most instances the Federal share is 65 percent. Greater State and local contributions could be required, both for initial construction and for maintenance, and Federal funding could be made conditional on adoption of stronger mitigation measures.

CHAPTER 4 REFERENCES

1. All-Industry Research Advisory Council, *Surviving the Storm: Building Codes, Compliance, and the Mitigation of Darnage (Oak* Brook, IL: AIRAC, 1989).
2. Anders, F., S. Kimball, and R Dolan, *Coastal Hazards* (Reston, VA: U.S. Geological Survey, 1989) (map with accompanying text).
3. Anonymous, "Are We Heading into an Era of More Intense Hurricanes?" *Climate* Alert, vol. *5, No. 3,* July-August 1992.
4. Apteker, L., "A Comparison of Bi-Coastal Disasters of 1989," San Jose State University, 1990.
5. Bea, K., *FEMA and the Disaster Relief Fund, report* for Congress, 94425 GOV (Washington DC: Congressional Research Service, May 7, 1992).
6. Beatley, T., *Hurricane Hugo and Shoreline Retreat: Evaluating the Effectiveness of the South Carolina Beachfront Management Act, final report* to the National Science Foundation, September 1992.
7. Beatley, *T.*, "*Risk* Allocation Policy *in the* Coastal Zone: The Current Framework and Future Directions," contractor paper prepared for the Office of Technology Assessment, February 1993.
8. Booth, W., "Pre-Andrew Mistakes Are Being Reheated. Grand Jury Warns," *The Washington Post, Dec. 1511~.* '

COASTS-FIRST STEPS

- **Revamp the National Flood Insurance Program**
  - -Direct FEMA to identify and map non-flood-related erosion zones.
  - —Mandate erosion-management standards.
- **Improve disaster assistance**
  - —Require States and localities to adopt mitigation measures as a condition of disaster assistance.
  - —Review and, if necessary, revise the criteria used by the President to declare disasters.
- Strengthen coastal zone management
  - —Mandate stronger risk-reduction measures when Coastal Zone Management Act is reauthorized.
  - —Consider implementing a coastal hazards-management program.
- Promote public education
  - -Authorize and fund education programs to foster greater knowledge about coastal erosion, sea level rise, flooding risks, and other topics.
- **Require increased State and local contributions to beach-nourishment operations**
  - -Redistribute the costs more evenly between the Federal Government (currently paying 65 percent) and the States.

9. Brewer, D., et al., *Evaluation of the National Coastal Zone Management Program (Newport,* OR: National Coastal Resources Research and Development Institute, 1991).
10. Burby, R., "Reforming Relief: An Invited Comment, " Natural *Hazards Observer,* vol. XV, No. 1, September 1990.
11. Burby, R., with B. Ciglar, S. French, E. Kaiser et al., *Sharing Environmental Risks: How to Control Governments' Losses in Natural Disasters,* (Chapel Hill, *NC:* Center for Urban and Regional Studies, University of North Carolina, 1990).
12. Cely, J., "Wildlife Effects of Hurricane Hugo," *Journal of Coastal* Research, No. 8, 1991.
13. Clark, K., "Predicting Global Warming's Impact," *Contingencies* (newsletter of Applied Insurance Research, Inc., Boston, MA), May/June 1992.
14. Congressional Research Service, *A Descriptive Analysis of Federal Relief, Insurance, and Lass Reduction Programs for Natural Hazards,* a report prepared for the Subcommittee on Policy Research and Insurance of the Committee on Banking, Finance and Urban Affairs, U.S. House of Representatives (Washington, DC: U.S. Government Printing Office, 1992).
15. Culliton, T., et al., *Fifty Years of Population Growth Along the Nation's Coast, 1960-2010* (Rockville, *MD:* National Oceanic and Atmospheric Administration, 1991).
16. Daniels, R., V. Gornitz, A. Mehta, S. Lee, and R. Cushman, *Adapting to Sea-LevelRise in the U.S. Southeast: The Influence of Built Infrastructure and Biophysical Factors on the Inundation of Coastal Areas (Oak* Ridge, TN: Oak Ridge National Laboratory, 1992).
17. Davison, A., "The National Flood Insurance, Mitigation, and Erosion Management Act of 1991: Background and Overview," in: *New Directions in Beach Management* (Tallahassee, *FL:* The *Florida* Shore and Beach Preservation Association% 1992).
18. Davison, A., "The National Flood Insurance program and Coastal Hazards," paper presented at the Coastal Zone '93 conference, New Orleans, LA, July 1993.
19. Duffy, K., "Hurricane Hugo: A Review of the Research," City of Charleston SC, November 1991.
20. Emmanuel, K., "The Dependence of Hurricane Intensity on Climate," *Nature,* vol. 326, No. 6112, Apr. 2, 1987.
21, Federal Emergency Management Agency, "Projected Impact of Relative Sea Level Rise on the National Flood Insurance Program," October 1991.
22. Federal Emergency Management Agency, "Statement of Operations," as of Sept. 30, 1992.
23. Federal Emergency Management Agency, "Estimating Probabilities of Exceeding Given Levels of Flood Insurance Losses in a One Year Period," Aug. 4, 1992.
24. Federal Emergency Management Agency (FEMA), National *Flood Insurance Program Community Rating System Coordinators Manual* (Washington, *DC: FEM.&* July 1992).
25. Federal Emergency Management Agency (FEMA), *Interagency Hazard Mitigation Survey Team Report on the Northeaster Storm, FEMA* 973-NJ-DR (Washington, *DC:* FEMA, January 1993).
26. Federal Insurance Administration, "Report to Stockholders," 1992.
27. Friedman, *D., Estimation of the Loss Producing Potential of the Wind and Hail Perils to Insured Properties in the United States* (London, England: Insurance and Reinsurance Research Group, Ltd., 1987).
28. Friedman, D., Natural Hazards Research Program, Travelers Insurance Co., 'Estimation of Damage-Producing Potentials of Future Natural Disasters in the United States Caused by Earthquakes and Storms,' paper presented at the International conference on the Impact of Natural Disasters, Los Angeles, CA, 1991.
29. Gardner, L., *et al., "Ecological* Impact of Hurricane Hugo—Salination of a Coastal Forest" *Journal of Coastal Research, No. 8, 1991.*
30. *Gardner,* L., et al., "The Geomorphic Effects of Hurricane Hugo on Undeveloped Coastal Landscape at North Inlet, South Carolina," *Journal of Coastal Research,* No. *8,* 1991.
31, Godschalk, D., Impacts *of the Coastal Barrier Resources Act: A Pilot Study* (Washington DC: Office of Ocean and Coastal Resource Management, National Oceanic and Atmospheric Administration, *1984).*
32. Godschalk, D., "The 1982 Coastal Barrier Resources Act: A New Federal Policy Tact," in: Cities *on the Beach,* Platt (cd.) (Chicago: University of Chicago, 1987).
33. Godschalk, D., and K. Cousins, "Coastal Management: Planning on the Edge, " *Journal of the American Planning Association, vol.* 51, 1985.
34. Godschalk, D., D. Brewer, and T. Beatley, *Catastrophic Coastal Storms: Hazard Mitigation and Development Management* (Durham, *NC: Duke* University Press, 1989).
35. Gornitz, V., T. White, and R Cushman, "Vulnerability of the U.S. to Future Sea Level Rise," in *Proceedings of the 7th Symposium on Coastal and Ocean Management, American Society* of Civil Engineers, Long Beach, CA, July 8-12, 1991.
36. Haarsma, R., J. Mitchell, and C. Senior, "TropicalDisturbances in a GCM," Climate Dynamics, 1992.
37. Hebert, P., J. Jarrell, and M. Mayfield, *The Deadliest, Costliest, and Most Intense United States Hurricanes of this Century (and Other Frequently Requested Hurricane Facts) (Coral Gables, FL: National* Hurricane *Center,* 1992).
38. Houlahan, J., "Comparison of State Coastal Setbacks to Manage Development in Coastal Hazard Areas," *Coastal Management,* vol. 17, 1989.
39. Houston, J., "Beachfill Performance," *Shore and Beach,* July 1991.
40. Intergovernmental Panel on Climate Change, Response Strategies working Group, coastal Zone Management subgroup, *Global* Climate Change and *the Rising Challenge of the Sea* (The *Hague: Ministry* of Transport, 1992).
41. Joint Task Force on the Hazard Mitigation Grant Program, *The Hazard Mitigation Grant Program: An Evaluation Report,* prepared by the National Emergency Management Association the Association of State Floodplain Managers, and the Federal Emergency Management Agency, September 1992.
42, Jones, E., and W. Stolzenberg, "Building in Coastal Barrier Resource Systems" (Washington DC: National Wildlife Federation, 1990).
43. Kana, T., *Conserving South Carolina Beaches Through the 1990s: A Case for Beach Renourishment* (Charleston SC: South Carolina coastal council, 1990).

44. Kana, F., D. Stevens, and G. Lennon, "Beach and Dune Restoration Following Hugo," *Shore and Beach,* vol. 58, No. 4, 1990.

45. Klarin, P. and M. Hershman, "Response of Coastal Zone Management programs to sea Level Rise in the united state%" *Coastal Management,* vol. 18, 1990.

46. Knott, D., and R. Mastore, "The Short-Term Effects of Hurricane Hugo on Fishes and Decapon Crustaceans in the Ashley River and Adjacent Marsh Creeks, South Carolina," *Journal of Coastal Research, No. 8,* 1991.

47. Larson, L., "Floodplain Managcream The Gap Between Policy and Implementation or Principle and Practice," *Water Resources Update, No. 90, winter* 1993.

48. Leatherman, s., "Impact of Accelerated sea Level Rise on Beaches and Coastal Wetlands," in: Global Climate *Change Linkages,* J. C. White (cd.) (Amsterdam, The Netherlands: Elsevier Science Publishing, 1989).

49. Leatherman, s., "National Assessment of Beach Nourishment Requirements Associated with Accelerated Sea Level Rise," in: *The Potential Effects of Global Climate Change on the United States: Appendix B-Sea Level Rise,* J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1989).

50. Lehman, H., "Accord Ends Fight Over Use of Land," *Washington Post,* Section E, July 17, 1993.

51. Lins, H., *Patterns and Trends of Land Use and Land Cover on Atlantic and Gulf Barrier Islands,* USGS Professional Papa 1156 (Washington, DC: U.S. Geological Survey, 1980).

52. *Maine,* state of, Department of Environmental Protection, Natural *Resources Protection Act: Coastal Sand Dune Rules,* January 1991.

53. Manning, B. "Building Codes and Enforcement by coastal *States and* Territories of the United States," in: *America's Vanishing Coastlines, National Committee on* Property Insurance, *1988.*

54. Millemann, B., *And Two if by Sea: Fighting the Attack on America's Coasts* (Washington, *DC: Coast* Alliance, 1986).

55. Miller, H., *Turning the Tide on Wasted Tax Dollars: Potential Federal Savings from Additions to the Coastal Barrier Resources System* (Washington, *DC:* National Wildlife Federation, April 1989).

56. Miller, H., "On the Brink: Coastal Location and Relocation Choices," in: *Coastal Erosion, Has Retreat Sounded* R. Platt et al. (eds.) (Boulder, CO: Institute of Behavioral Sciences, university of Colorado, 1992).

57. Musham, c., "Charleston After Hugo: A Study of Post-Hurricane Attitudes, Perceptions, and Behavior of Tri-County Area Residents," prepared for Hotline and the Trident United way, 1990.

58. National Committee on Property Insurance, *America's Vanishing Coastlines, October 1988.*

59. *National* Research Corn@ *Managing CoastalErosion* (Washington, *DC: National* Academy Press, 1990).

60. National Research Council, Marine Board Commission on Engineering and Technical Systems, *Responding to Changes in* Sea *Level, Engineering Implications* (Washington, *DC:* National Academy press, 1987),

61. North Carolina Division of Coastal Management, *A Guide to Protecting Coastal Resources Through the CAMA Permit Program* (Raleigh, *NC: North Carolina* Division of Coastal Management, 1988).

62. Park, R., "The Effects of Sea Level Rise on U.S. *Coastal* Wetlands, in: *The Potential Effects of Global Climate Change in the United States: Appendix B—Sea Level Rise,* J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1989).

63. Park, R, M. Trehan, P. Mausel, and R Howe, *The Effects ofSea LevelRise on U.S. Coastal Wetlands and Lowlands,* HRI *Report No.* 164 (Indianapolis, IN: Holcomb Research Institute, Butler university, 1989).

64. Peltier, W., and A. Tushingham, "Global Sea Level Rise and the Greenhouse Effect: Might They Be Connected?" *Science,* vol. 244, 1989, pp. 806-810.

65. Perry, D., et al., *Hurricane Andrew-Preliminary Observations of WERC Post-Disaster Team (College* Station, *TX:* Wind Engineering Research Council, September 1992).

66. Pilkey, O., "The Engineering of Sand," *Journal of Geological Education,* vol. 37, 1989.

67. Pilkey, O., and T. Clayton, "Beach Replenishment: The National Solution?" *Coastal Zone '87, American Society* of Civil Engineers, 1987.

68. Pito, V., "Accelerated Sea Level Rise and Maryland's Coast: Addressing the coastal Hazards Issue," paper presented at the annual meeting of the Coastal Society, Washington DC, April 1992.

69. Platt, R., "Life After Lucas: 'he Supreme Court and the Downtrodden Coastal Developer," *Natural Hazards Observer,* September 1992.

70. Platt, R, T. Beatley, and H. Miller, "The Folly at Folly Beach and Other Failings of U.S. Coastal Erosion Policy," *Environment,* November 1991.

71. Platt, R, H. Miller, T. Beatley, J. Melville, and B. Mathenia (eds.), Coastal *Erosion: Has Retreat Sounded?* (Boulder, CO: Institute for Behavioral Sciences, University of Colorado, 1992).

72. Property Claim Services, A Division of American Insurance Services Group, Inc., "Hurricane Andrew's Estimated Cost to Property Insurers Revised to $15.5 Billion by Property Claim services," February 1993 (press release),

73. Reid, W., and M. Trexler, *Drowning the Natural Heritage: Climate Change and U.S. Coastal Biodiversity* (Washington, *DC:* World Resources Institute, 1991).

74. Reilly, F., Deputy Federal Insurance Administrator, Federal Insurance Administration testimony at hearings before the Subcommittee on Consumer credit and Insurance, House Banking, Finance, and Urban Affairs, June 24, 1993,

75. Rogers, S., P. Sparks, and K. Sparks, "A Study of the Effectiveness of Building Legislation in Improving the Wind Resistance of Residential Structures," National Committee on Property Insurance, 1988.

76. St. Amand, L., "Sea Level Rise and Coastal Wetlands: opportunities for a Peaceful Migration," *Environmental Affairs,* vol. 19,1991.

77. Salveson, D., *Wetlands: Mitigating and Regulating Development Impacts (Washington DC:* Urban Land Institute, 1990).

78. Showalter, P., W. Riebsame, and M. Myers, "Natural Hazard Trends in the United States: A Preliminary Review for the 1990s," Working Paper 83 (Boulder, CO: Natural Hazards Research and Applications Information Center, university of Colorado, February 1993).
79. Simmons, M., "National Flood Insurance Program Issues," congressional Research Service Issue Brief, December 1992.
80. South Carolina Budget and Control Board, Division of Research and statistical Services, Office of Economic Research, "Economic Impact of Hurricane Hugo," January 1991.
81. Titus, J., "Greenhouse Effect and Coastal Wetland Policy: How America Could Abandon an Area the Size of Massachusetts," *Environmental Management,* November/December 1991,
82. Titus J., and M. Greene, "An Overview of the Nationwide Impacts of Sea Level Rise," in: *The Potential Effects of Global Climate Change on the United States: Appendix B—Sea Level Rise,* J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1989).
83. Titus, J., R Park, S. Leatherman et al., "Greenhouse Effect and Sea Level Rise: The Cost of Holding Back the Sea," *Coastal Management, vol.* 19, 1991.
84. U.S. Army Corps of Engineers and Federal Emergency Management Agency, Region IV, "Hurricane Hugo Assessment," January 1990.
85. U.S. Army Corps of Engineers, "south Carolina Shores—North Portion—Charleston, Georgetown, and Horry Counties, S.C.," June 1991.
86, us. Army corps of Engineers, Institute for Water Resources, "IWR Review Report for U.S. Congress, Office of Technology Assessment, in Reference to Draft Report on Systems at Risk from climate Change," IWR Policy Study 93-PS-1, July 1993.
87. U.S. Congress, General Accounting Office (GAO), Flood *Insurance: Information on the Mandatory Purchase Requirement,* RCED-90-141FS (Washington, DC: GAO, Aug. 22, 1990).
88. Us. Congress, General Accounting Office (GAO), Coastal *Barriers: Development Occurring Despite Prohibition Against Federal Assistance,* GAO/RCED-92-115 (Washington, *DC:* GAO, July 1992).
89. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, *Biennial Report to Congress on Coastal Zone Management* (Washington, DC: Office of Ocean and Coastal Resource Management, April 1990).
90. U.S. Geological Survey (USGS), "Coastal Hazards," National *Atlas of the United States of America* (Reston, VA: USGS, 1985) (map).
91. Vallianos, L., "The Federal Interest in Shore Protection," unpublished report for the Institute for Water Resources, U.S. Army Corps of Engineers, R. Belvoir, VA, 1991.
92. Virginia Water Control Board, "Virginia Revolving Loan Fund: Program Design Mare@" Richmond, VA, revised July 1991.

Water | 5

Status

- Competition for high-quality water is increasing due to population grow@ concerns for the environment, and assertion of new water rights.
- Significant water-quality problems; urban water infrastructure aging; ground water overdraft is a problem in some areas.

Climate Change Problem

- **Changes** in water availability could add stress to already strewed systems.
- Changes in the frequency, duration, or intensity of floods and droughts could occur.

What Is Most Vulnerable?

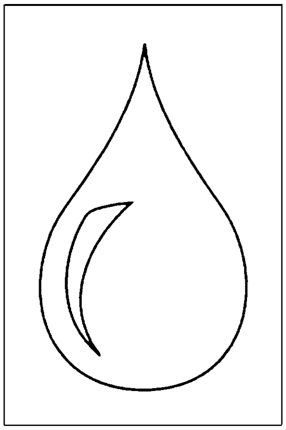
- **Parts of the Nation already experiencing considerable stress (e.g., many parts of the Southwest and South Florida).**
- **Areas where competition for water is expected to increase.**
- **The central part of the United States, which many scientists expect to become hotter and drier.**

Impediments

- Rigid and inefficient institutions.
- **Fragmented and uncoordinated management.**
- **Traditional engineering solutions less acceptable economically and environmentally.**

Types of Responses

- Promote contingency planning for floods and droughts.
- Improve supply management (e.g., by improve coordination, using ground and surface water conjunctively, improving reservoir and reservoir-system management).
- Facilitate water marketing and other transfers.
- Promote use of new analytical tools.
- Improve demand management (e.g., pricing reform and conservation).
- Augment supplies (e.g., by adding reservoirs and building desalination plants).



OVERVIEW

Fresh water is an integral element of all the systems discussed in this two-volume report. Its abundance, location, and seasonal distribution axe closely linked to climate, and this link has had much to do with where cities have flourished, how agriculture has developed, and what flora and fauna inhabit a region. The potential for climate change to affect, first, the current status of the Nation's water resources and, second, those systems that depend on water, is of considerable long-term importance. Exactly how climate change will affect water resources, especially regionally, is still unknown. Although it is unlikely that the droughts, floods, and hurricanes that have been so much a part of the news in the past few years can be linked to a changing climate, they illustrate the kind of extreme events that climate change may make more common in the future.

Climate change, then, is an additional factor to consider in water resource planning. A variety of other factors is clearly straining the Nation's water resources and leading to increased competition among a wide variety of different uses and users of water. Human needs for water are increasingly in conflict with the needs of natural ecosystems. The stress is particularly obvious in the West, where a high percentage of available supplies has already been developed in some areas, but examples of conflict among uses for scarce, high-quality water occur throughout the country.

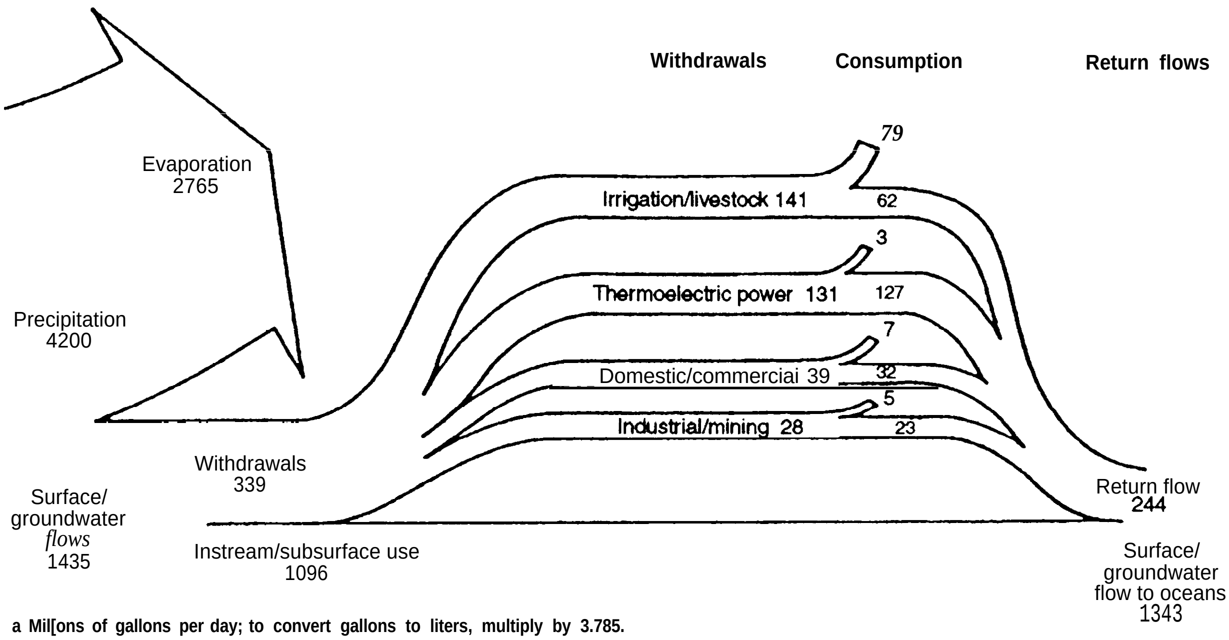
The Nation faces a considerable challenge in adapting its water resource systems to these numerous current and potential stresses. Among other things,

- Traditional engineering solutions for developing additional supplies have become less acceptable.
- Many institutions are ill-designed to cope with scarcity in water resources.
- Few incentives exist to conserve water.
- Responsibilities among Federal agencies often overlap or conflict.
- Coordination between levels of government can be inadequate.
- Flood- and drought-related costs amount to hundreds of millions of dollars each year and continue to increase.

Major changes are occurring in the way water resource problems are addressed. The management of existing resources is taking on increasing importance as the potential for developing new supplies declines. Similarly, reallocating water through markets from lower- to higher-valued uses is becoming more common. Promising practices beginning to be used include conservation, pricing reform, resenvoir-system management, marketing and transfers, conjunctive management of ground and surface water, wastewater reclamation, and river basin planning. These practices promote greater flexibility and/or efficiency in water resource management which will help enable water resource systems to cope with uncertainty and adapt to any climate change. Necessary improvements in the management of water resources do not, however, come easily: proposed changes often create losers as well as winners, so many politically sensitive debates can be expected.

Stresses on water resources are most acute and visible during extreme events such as floods and droughts. The Nation's approaches to dealing with such events have generally proven to be unsatisfactory and expensive. Policies that improve the ability to cope flexibly and efficiently with floods and droughts would be valuable now and would help prepare the Nation for a less-certain future. It is difficult to know whether the recent 6 years of drought in the western United States are a rare but possible outcome of natural climate variability, an early indication of climate change, or a return to the average climate after a long, particularly wet spell. Longer climate records are needed to distinguish among these various possibilities. Regardless of the cause of recent droughts, improving plarnning for and management of extreme events should be a high priority for the Federal Government.

Figure %1—Water Withdrawals and Consumption In the Coterminous United States, 1985[a]



a Mil[ons of gallons per day; to convert gallons to liters, multiply by 3.785.

SOURCE: Adapted from W. Solley, R. Pierce, and H. Perlman, Estimated Use *of Water the United* States *in1990,* USGS Survey Circular 1081 dependent on water (e.g., fishing and sailing) or enhanced by it (e.g., camping),[4] and the demand for water-related recreation is growing (79). Substantial amounts of water are used for cooling fossil fuel and nuclear power plants. Finally, water dilutes and/or helps carry away pollution that either intentionally or unintentionally reaches the Nation's rivers, lakes, and estuaries.

Throughout the country, stress on water supplies is increasing, and many of the uses for water are being (or could eventually be) affected in one or more regions. The increasing stress is especially obvious in arid and semiarid parts of the country where water is not abundant, but is also apparent in many nonarid areas as well. Population growth in some areas has stimulated increased demand for water and has been ultimately responsible for many water-quality problems, groundwater overdraft, and saltwater intrusion into some freshwater aquifers.

Additionally, groups whose water rights were not previously represented or asserted are beginning to compete for water with traditional users. In particular, as more water is diverted from streams for human purposes, concern has grown about the need to reserve water for environmental purposes. Several States now recognize rights to *instream flow* (i.e., rights to retain water in the stream channel) or have minimum-flow requirements to protect fish and wildlife, and water left in streams is no longer considered wasted. Similarly, entities such as American Indian tribes, whose water rights have been inadequately recognized in the past, are beginning to claim their rights. In many cases, unused Indian water rights are senior to the rights of those who now divert the water. The new competitors, plus a growing population, will all draw from the same basically fixed supply of water.

Many of the Nation's water institutions (e.g., doctrines, laws, administrative procedures, and compacts), first established when water use was low, are proving unable to cope with increasing competition amid greater relative scarcity. In particular, many existing institutions lack the flexibility required to ease adjustment to changing circumstances. Finally, much of the Nation's water infrastructure is aging. High leakage rates, for example, are common in urban water systems, and many of the country's reservoirs need reconditioning.

Climate change cannot yet be counted among the reasons water resource systems are under stress. Moreover, demographic and technological changes are likely to have a greater effect on water management in the near term than climate change. However, climate change does have the potential to seriously affect some water supplies, further stressing already stressed water resource systems.

POSSIBLE EFFECTS OF A WARMER CLIMATE ON WATER RESOURCE SYSTEMS

The hydrological cycle, depicted in figure 2-12, traces the cycling of water in the oceans, atmosphere, land and vegetation, and ice caps and glaciers. Exchanges of water among these elements occur through precipitation, evapotranspiration, and stream and groundwater flow. The hydrological cycle has an important role in the global climate system and both affects climate and is affected by it (8).

Most scientists agree that global warming will intensify the hydrological cycle (31). The increase in global average temperatures anticipated for a doubling of greenhouse gases[5] could increase average global precipitation from 7 to 15 percent and evapotranspiration between 5 and 10 percent (62). Increases in temperature, precipitation, and evapotranspiration would, in turn, affect stream runoff and soil moisture, both very important to human and natural systems. Average global runoff would be expected to increase, but general circulation models (GCMS) do not relia-

[4] The figure is a combined one for fresh and salt water.

[5] Most scientists accept 1.5d4.5'C (2.7 and 8.2 °F) as the range for an "effective CO_2 doubling" (32); see chapter 2 for more discussion.

bly predict how much (62). Certain models predict that precipitation will increase in some regions, whereas others suggest it will decrease (48). The range (and therefore the uncertainty) in the models' predictions of soil moisture and runoff is even greater than it is for precipitation (34).

Most important to water resource planners is how global warming will affect key variables regionally. A variety of factors, including local effects of mountains, coastlines, lakes, vegetation boundaries, and heterogeneous soil, is important in determining regional climate. Currently, GCMS cannot resolve factors this small because the grid they use-blocks of 155 to 620 square miles-is too large (80).

Climate modelers generally agree that a first likely consequence of climate change is that precipitation will increase at high latitudes and decrease at low to middle latitudes (where the water-holding capacity of the atmosphere will be largest (18)). Thus, in the midcontinent areas, especially in summer, evapotranspiration could exceed precipitation, and soil moisture and runoff would decrease. The potential for more-intense or longer-lasting droughts would, therefore, increase (58).

A second likely consequence is changes in the type and timing of runoff. Snowmelt is an important source of runoff in most mountainous areas. Warmer temperatures in such areas would cause a larger proportion of winter precipitation that now falls as snow to fall as rain. Thus, the proportion of winter precipitation stored in mountain snowpacks would decrease. Winter runoff would increase, and spring runoff would subsequently decrease. During times when flooding could be a problem, a seasonal shift of this sort could have a significant impact on water supplies because to maintain adequate storage capacity in reservoirs, early runoff would probably have to be released (40). Many Western States (e.g., California and Colorado) depend on the late spring snowmelt as a major source of water. Runoff filling reservoirs early in the spring means that less stored water would be available during summer, when demand is highest. The California Department of Water Resources has estimated, for example, that if average temperatures warm by 3 ‘C (5.4 oF), winter snowmelt runoff would increase, but the average April-July runoff would be reduced by about 30 percent.[6]

Sea level rise, a third likely consequence of global warming, could have effects on water supplies in some coastal areas. Higher sea level would cause a slight increase in saltwater intrusion of freshwater coastal aquifers, would create problems for levees protecting low-lying land, would increase the adverse consequences of storm surges, and might affect some freshwater intakes. (Effects of sea level rise on coastal structures and wetlands are discussed in detail in ch. 4 and in vol. 2, ch. 4.)

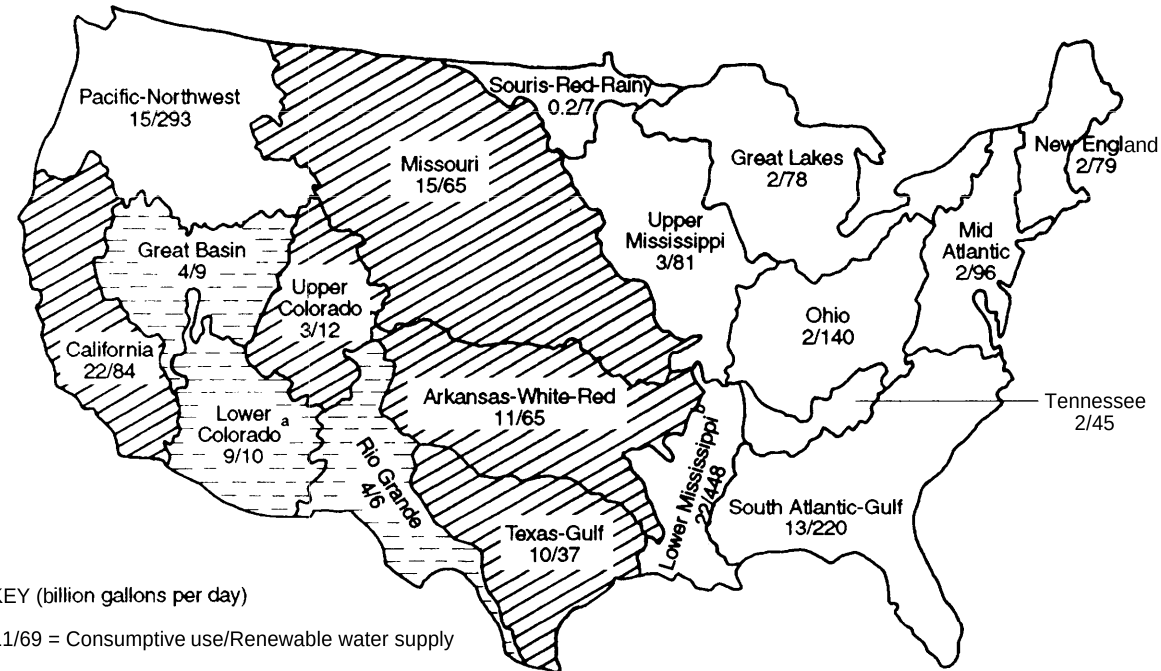
CURRENT AND POTENTIAL STRESSES ON WATER RESOURCE SYSTEMS

Introduction

Although scientists are not yet certain about the magnitude, direction, or timing of the regional impacts of global climate change, much can be said about current stresses on water resource systems. Climate change could, exacerbate the adverse effects of these stresses in some regions and alleviate them in others. However, areas that are already approaching limits for developing new water supplies or are under stress for other reasons should be particularly concerned about the possibility that climate change may further stress water resource systems and reduce the capability to adjust. Appendix A catalogs the major water resource problems for each of the 50 States.

[6] M. Roos, Chief Hydrologist, California Department of Water Resources, personal communication 1992.

Figure 5-2—Average Consumptive Use and Renewable Water Supply by Water Resource Region



KEY (billion gallons per day)

11/69 = Consumptive use/Renewable water supply

Consumptive use as a percentage of renewable supply

0-10 10-40 40-100

a Represents entire Colorado River Basin.
b Represnts entire Mississippi River Basin.

NOTE: To convert gallons to liters, multiply by 3.785.

SOURCE: W. Solley, U.S. Geological Survey, 1993,

Growing Population, Increasing Competition

Water is a renewable resource, but long-run average supplies are essentially fixed as long as climate fluctuates within a known range. The U.S. population, however, is steadily increasing. By 2010, the United States is projected to add about 35 million people to its 1993 population of roughly 256 million people. Total U.S. population is projected to grow about 7 percent over this decade, but the populations in the 10 fastest-growing States[7] will increase by 14 to 23 percent. Nine of these States are in the South and West, yet developed water-supply systems in many are already overburdened. Current demand for water relative to annual supply in all western river basins (except the usually well-watered Pacific Northwest) is 10 to 50 times higher than it is in the eastern half of the country, and some western basins have few undeveloped sources left (26). Figure 5-2 illustrates average consumptive use relative to renewable water supply in each of the water resource regions of the conterminous states.

Large western cities, like Los Angeles and San Diego, must import water from sources hundreds

[7] In order of decreasing projected growth rate, these arc Arizona, Nevada, New Mexico, Florida, Georgia, Alaska, Hawaii, New Hampshire, C& ifornia, and Texas (78).

of miles away. As a result of population growth, atisfying the demand of such cities is becoming more challenging, especially during drought. Despite considerable water-storage capacity in California, for example, many cities find it necessary to implement emergency-rationing procedures. Other fast-growing western cities-Las Vegas, Reno, Denver, El Paso, San Antonio, for e x a m p l ~e having problems ensuring adequate water supplies for the future. In the Southeast, population growth is becoming a problem for water-supply planners in Atlanta and in some cities in Florida.

The challenge for growing cities is to develop or acquire new sources of water and use the water they have more efficiently. Many opportunities exist for using water more efficiently, and some cities and States are addressing water-supply-related problems in creative ways (see the section Adapting Water Resource Systems to Climate and Other Changes, later in this chapter). However, a general and growing complication is that demands for water for use in cities can and increasingly do conflict with established or previously neglected demands for water for other purposes, including irrigation, fish and wildlife sustenance, ecosystem conservation, recreation, navigation, and power generation. Areas that become hotter and drier as a result of climate change would likely see competition among uses increase (see box 5-A).

Poor Water Quality

People also stress water systems when they permit pollutants to enter surface Water and subsurface groundwater.[8] Pollution can diminish supplies available for human consumption (sup plies that in some cases are already stressed by population growth) and can adversely affect fish and wildlife that depend on clean water. Surface waters may be contaminated by siltation, nutrients, salts, organic matter, and hazardous materials (94). Despite high-priority Federal and State efforts, many supplies of surface and groundwater are currently polluted.

Box 5-B describes water-quality problems affecting the Rio Grande. This river presents a particularly challenging set of problems because it flows through an arid region where water is much in demand and because it forms a 1,200-mile boundary between two sovereign countries, the United States and Mexico, that must work together to ensure the river's health.

During drought, when stream flows and lake levels are low, water temperatures are higher and pollutants are more concentrated (33). Low stream flows in estuarine areas also enable salt water to move further upstream, in some cases affecting freshwater supplies. For example, in 1988, drought-related salt intrusion into the Mississippi River Delta affected petroleum refineries at New Orleans, and fresh water had to be barged into operate boilers and to cool machinery (57). Rivers that normally carry high salinity loads, such as the Colorado, can be dramatically affected by decreased runoff. These problems would be exacerbated in parts of the country that become drier as a result of climate change.

Higher surface-water temperatures can be a problem for fish that depend on cold water for spawning, such as Chinook salmon. When optimal temperatures for salmon incubation are exceeded by only a few degrees, increases in mortality can be expected (l). In California's Sacramento River System, for example, a problem exists during dry years when reservoir levels are lower and water discharged from them is warmer than normal (35). A few newer dams have temperature-control outlets that allow water to be released from various depths, but retrofitting dams that do not have such controls is very expensive. Global warming may make it impossible to preserve some cold-water fish without providing artificial temperature controls at large dams that lack these controls (35). Conversely, some warm-

[8] Groundwater constitutes about 36 percent of municipal drinking-water supplies.

Box 5-A-Climate Change, Water Resources, and Limits to Growth?

Many cities of the Southwest-Las Vegas, Tucson, and Phoenix, for example—have beautiful green golf courses positioned like islands amidst seemingly endless expanses of parched desert. Although less likely now, it is still possible to see fountains shooting water, much of which evaporates, high into the airon scorching summer days. These are just two of the more obvious extravagant practices that people who have relocated from the well-watered eastern parts of the country brought with them as they settled the arid and semiarid parts of the American Southwest. Growing cotton and other water-intensive crops in such areas is another.

Many people are drawn to the Southwest by generally mild climates and outstanding recreational opportunities and by the new, dynamic potential for economic development. High growth rates have been typical, and the three U.S. States with the highest projected growth rates, Arizona, Nevada, and New Mexico, are all arid Western States. California much of which is arid, is now the most populous of the 50 States (78).

That continued growth and development of water-stressed areas of the United States is desirable is rarely questioned. Until recently, except perhaps for a few small settlements in out-of-the-way places, water has not been a limiting factor in western development. Where additional water has been needed to enable further growth, water managers have been able to find it-but now usually at increasingly long distances from where it is used or at greater depth in subsurface aquifers. Los Angeles, for example, imports significant portions of its water from sources hundreds of miles away-northern California, the Owens Valley, and the Colorado River. Without this additional water, Southern California would not be able to sustain the dramatic growth that has occurred there (at least given current usage patterns). San Diego, Las Vegas, Reno, Denver, El Paso, Phoenix, and many other cities, large and small, face similar challenges in acquiring enough water to sustain growth or in using what water they now have more efficiently.

Western author Wallace Stegner noted that aridity imposes limits on human settlement that can be ignored only at one's peril (68). So far, the impressive water infrastructure developed in the West during the past 100 years has enabled society to meet its water demand and push back these limits. Growth could be difficult to sustain without major and difficult adjustments. Explicit growth-control policies have been limited and generally very unpopular. Water issues, especially in the West, are usually framed in terms of how to accommodate urban growth and not how to adjust to limitations imposed by a harsh environment (70).[1] Nevertheless, it maybe prudent at least to consider the possibility that future severe water shortages in arid parts of the country will require strong and explicit growth-limiting policies in addition to implementation of other adaptive measures. Federal constitutional doctrines designed to promote the free flow of goods and people across State lines and the core principle of public utility law-that water providers have a duty to serve market demand (70)-imply that growth maybe difficult to restrict legally. Nevertheless, at some point in a possibly drier future, some industries and individuals may begin basing their decision to move to arid areas (or to stay in them) in part on the cost and availability of water. Such an occurrence would mark a fundamental shift in development and demographic patterns.

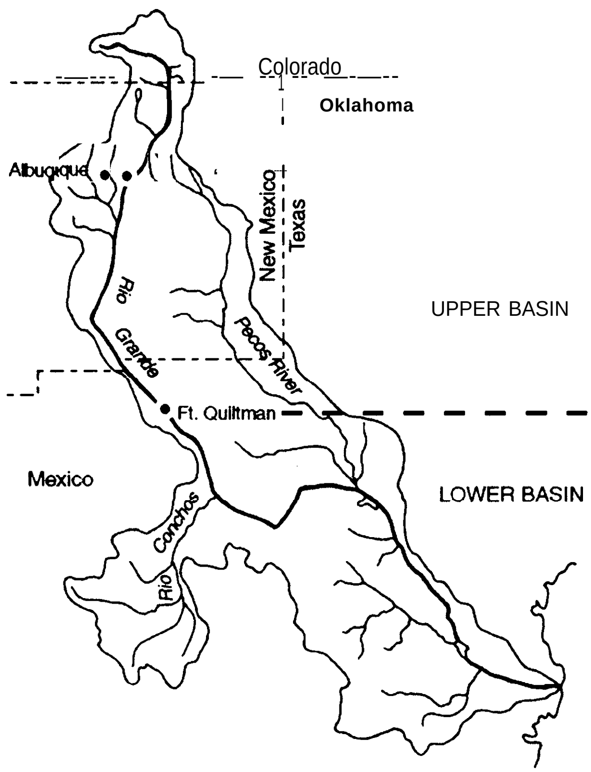
[1] A few policies do recognize limitations. Arizona, for example, requires developers to show that they have a 100-year water supply before they are allowed to build. Such policies, however, generally have not fundamentally called into question the desirability of continued growth. The Arizona policy has also had some unwanted side effects because it has encouraged cities to take extraordinary action to find water for continued long-term growth. As a result, the practice of "water farming" has developed. Some rural areas are being dewatered, and economic development in these areas has consequently been stifled.

Box 5-B-Water Quality, Climate Change, and the Rio Grande

Poor water quality is a problem in many parts of the country. However, in an arid region such as southwest Texas, where water is relatively scarce, water-quality problems can contribute significantly to water-supply problems. This water quality/water quantity connection is especially important in the lower Rio Grande Basin, where population growth, municipal and industrial expansion, and an increase in irrigation have dramatically increased the demand for water while negatively affecting water quality. Managing the water resources of the Rio Grande is especially difficult given the river's bi-national status.

The Rio Grande forms the border between Texas and Mexico for some 1,200 miles (1 ,935 kilometers)[1] and is one the most important rivers in North America. It originates in Colorado as a pristine alpine stream, but as it makes its way south and east to the Gulf of Mexico, it becomes a river under stress. Intensive municipal and industrial activities along its banks have resulted in tens of millions of gallons of sewage yearly entering the river. Agricultural runoff degrades water quality by contributing significant amounts of fertilizers and pesticides to the river. And natural discharges of highly saline groundwater contribute to salinity problems. In addition, a very high 72 percent of the renewable water supply of the basin is now consumed. This percentage is surpassed only in the Colorado River Basin and is dramatically greater than the single-digit percent of renewable supply consumed in most basins in the eastern United States. If current trends continue, consumption of water in the basin is likely to increase.

The Rio Grande Basin



SOURCE: W. Stone, M. Minnis, and E. Trotter (eds.), *The Rio Grands Basin: Global Climate Change Scenarios, New Mexico* Water Resources Research Institute Report No. M24, June 1991.

Climate change could exacerbate current water conflicts. Many western rivers, including the Rio Grande, would experience a significant reduction in dependable stream flow if average temperature increases. This effect would seriously threaten irrigated agriculture, industrial development, and drinking-water supplies in the region. Even if climate change leads to a decrease in agriculture in the lower Rio Grande Basin, industrial and municipal development, spurred by the North American Frw Trade Agreement (NAFTA), mght continue to place significant demands on the river in a warmer climate. The combined effects of climate change and more-direct human-caused stresses would pose a considerable adaptation challenge.

The Rio Grande's drainage basin is separated into northern and southern regions encompassing a total of 182,215 square miles of arid to semiarid land in southern Colorado, New Mexico, Texas, and Mexico. Some 2.7 million people live in the basin and depend on its water. Precipitation ranges from 10 inches (25 cm) per year in the western part of the basin to up to 24 inches (60 cm) per year along the Gulf Coast, but annual evaporation exceeds

[1] To convert miles to kilometers, multiply by 1.609.

(Continued on next page)

Box 5-B–Water Quality, Climate Change, and the Rio Grande-(Continued)

precipitation in much of the region. Many parts of the area rely on ground water to supplement scarce surface water supplies, and groundwater overdraft is a problem in parts of the region. Concern about droughts and flooding has led to the construction of dams and levees, so the once highly variable flow of the river is now moderated. Stored surface water is the principle source of supply in the western part of the basin, but the lower part of the basin depends almost entirely on surface water due to the poor quality of ground water in the area.

Historically, the Rio Grande Basin has supported a predominantly agrarian economy. Many of the crops grown in the valley are very water-intensive, including cotton, rice, and sugar cane. To northerners, the region is known as the "winter garden" because it supplies the country with voluminous amounts of citrus fruits and vegetables during winter months (see ch. 6). The Rio Grande is almost completely diverted at Juarez/El Paso to support irrigated agriculture in the southern part of the basin. (Return flows and more southerly tributaries supply water to the river below this point.)

Low flows and surface-water shortages have become a problem in the basin, as have increases in salinity in groundwater. To date, farmers have been more concerned with water shortages than with increasing salinity. Salt buildup in the soil, however, is certain to affect future production and may force abandonment of some agricultural lands. Runoff laden with pesticides, fertilizers, and sediment reaches the river and further impedes water quality. Moreover, reduced flows mean that less water is available to dilute pollutants, so their concentration in the river increases during low-flow periods.

Municipal and industrial demands on the river are growing dramatically, driven by the region's burgeoning population growth. A significant increase in growth is occurring in the so-called "colonias" that have been established along the border. These communities, which are home to many hundreds of thousands of people, generally lack sewage systems, wastewater treatment plants, and potable water. Wastewater in some cases is discharged directly into irrigation canals, which ultimately supply water for some crops. This lack of infrastructure, including overflowing and inadequately lined waste dumps, has resulted in a high incidence of infectious diseases (e.g., hepatitis and cholera), contamination of groundwater, and clogging of storm-water systems. Industrial operations exacerbate these problems by discharging wastewater directly into the river. As a result, water quality is so low in the eastern part of the basin that only 1 percent of the water is fit for agricultural or municipal use. All of these impacts have severely degraded water quality in the river, and, given the limited supply, could present serious water-allocation problems in the future. Changes in management practices will ultimately be required on both sides of the border.

The international boundary created by the Rio Grande separates much more than land mass: it represents the often dramatic division of first and third world nations. The socioeconomic differences that exist between the two countries are deeply rooted. Some of the poorest U.S. counties with some of the fastest-growing populations are along this border. These communities generally experience depressed economies, poverty-level incomes, short life expectancy, low levels of education, and high population mobility. Much of the economy is based on providing food for other parts of the United States. Economic conditions in Mexico are even worse. Such conditions make the development of sound water-management policies and the development and enforcement of regulations to sustain human and ecosystem health much more difficult.

Wildlife and migratory bird populations also rely on the river, but maintaining stream flow for environmental purposes is not always possible because of competing demands for the water, and it will likely become even more difficult in the future.

Conservation, recycling, shifting to dryland farming, changing water pricing, and establishing water-master programs for the basin are among the approaches that could be used to address present and future water-quality and -quantity problems. Focusing on improving water quality may be one way of assisting adaptation to climate change that would be especially appropriate in the arid Rio Grande Basin.

SOURCES: This box is drawn largely from J. Schmandt and G, Ward, *Texas and Global Warming: Water Supply and Demand in Four Hydrological Regions* **(The University of Texas at Austin: The Lyndon Baines Johnson School of Public Affairs, 1991); W. Stone, M. Minnis, and E. Trotter (ads.),** *The Rio Grande Basin: Global Climate Change Scenarios,* *New* **Mexico Water Resources Research Institute Report No. M24, June 1991.**

water fish populations are likely to benefit from temperature rises associated with global warming as their thermal habitat expands (52).

The contamination of groundwater is a particularly troublesome problem; once an underground aquifer becomes contaminated, its value is impaired or lost for a long time. Fertilizers and pesticides, effluent from various manufacturing processes, leakage from underground storage tanks, and oil spills can all find their way into groundwater. The extent of groundwater pollution in the United States is not known precisely, but some groundwater contamination occurs in every State, and the Environmental Protection Agency (EPA) has identified close to 1,000 hazardous-waste sites that have contributed to groundwater contamination (10). The Northeast has groundwater problems associated with industrial waste, petroleum products, and landfill leachate, and many farming States have problems arising from agricultural practices.

Groundwater can also be contaminated by saltwater intrusion-particularly in coastal States. In some cases, intense groundwater pumping has allowed salt water to intrude into coastal aquifers. For example, Orange County, California, now injects treated, recycled surface water into its coastal aquifer to keep salt water from intruding. Miami has spent millions trying to repel saltwater intrusion. Sea level rise will enable salt water to penetrate somewhat further into coastal aquifers (80).

Many water-quality problems will be addressed in 1993 and 1994, when Congress considers reauthorizing the Clean Water Act (P.L. 92-500). The Water Pollution Prevention and Control Act of 1993 (S. 1114) was introduced in June 1993 and will likely serve as the main vehicle for considering changes in the Nation's water-pollution laws. Box 5-C describes some key issues being considered.

Environmental Water Allocation

The value of water for environmental uses (e.g., for preserving aquatic species and habitat) has typically been neglected in developing water resources for consumptive purposes (16). In the early part of the 20th century, water was often considered wasted if it was allowed to remain in a stream and not put to some "beneficial' use. Diverting water from a stream was not especially a problem for instream requirements as long as enough water was available. However, the effect of diversions on instream environmental uses has increased as more and more water has been developed for consumption. Over the past 20 years, popular awareness of the environment and the desire to protect it have increased. Thus, an important new competitor for water (or at least one with increasing clout) is the environment: water used for protection of wetlands, fisheries, and endangered species or for preservation of the wild and scenic status of a river cannot be simultaneously available for offstream, consumptive uses like irrigation and domestic supply.

The potential for conflict between instream and other uses of water is high. California's Central Valley farmers, for example, vigorously (but unsuccessfully) opposed a provision of the recently enacted Central Valley Project (CVP) Improvement Act (P.L. 102-575) that requires 800,000 acre-feet (af)[9] of project water to be reallocated or set aside for fish, wildlife, and habitat restoration. Similarly, South Florida's demands for water for the environment (e.g., for restoring the Everglades) are in growing competition with water for humans (see box l-D). Notably, the Endangered Species Act (P.L. 93-205) has become a powerful preservation tool in recent years, and many water resource managers are concerned that vigorous enforcement of this act to protect water-dependent species will in-

[9] One acre-foot (af) equals 325,851 gallons of water (43,560 cubic feet, or 1,234 cubic meters), the amount of water it takes to cover 1 acre to a depth of 1 foot. It is enough water to sustain two average households for a year, To convert from acre-feet to cubic meters, multiply by 1,234!

Box 5-C-Reauthorizing the Clean Water Act

The Clean Water Act (CWA; P.L. 92-500), formally known as the Federal Water Pollution control Act of 1972, is the Nation's foremost piece of water-quality legislation. The ambitious goai of the original act was to restore polluted waters throughout the Nation to a "fishable, swimmable status" by 1983, to eliminate discharges of pollutants into navigable waters, and to prohibit the discharge of toxic pollutants in toxic amounts. Two major strategies for achieving these goals included establishment of a Federal grant program to heip local areas build sewage treatment plants and a requirement that all municipal sewage and industrial wastewater be treated before it is discharged into waterways (1 1). The comprehensive act specifies technology-based effluent limitations and standards, receiving-water-quality standards, and a discharge permit system.

The Nation has made considerable progress in cleaning up polluted waters since 1972. Some $540 billion has been spent on water-pollution control (36). Currently, more than 37 billion gallons (140 billion liters)[1] of wastewater are treated daily, and about 15,500 wastewater treatment facilities and dose to 20,000 collection systems operate in the United States. Eighty-nine percent of waste treatment facilities now provide secondary or advanced treatment (11).2 As a result, Conventional pollutants such as bacteria and oxygendernanding materials have diminished. Nevertheless, and despite major amendments to the CWA in 1977, 1981, and 1987, some significant water-quality problems remain. Sedimentation, nutrient enrichment, runoff from farmlands, and toxic contamination of bottom sediments are proving to be more persistentprobiems(11).

The Clean Water Act will likely be reauthorized again during the 103d Congress inan attempt to address these continuing problems. S. 1114, the Baucus-Chafee Water Pollution Prevention and control Act, has emerged as the primary legislative vehicle for revising water-quality iaw. The bill revisits such key issues as watershed planning, control of non-point-source pollution and of toxic discharges, and funding for municipal wastewater treatment facilities.

Watershed planning—S. 1114 encourages states to adopt watershed-pianning programs. A watershed generally is defined as a region that lies between two ridges of high iand and drains into a river, river system, or other body of water. Watershed planning refers to efforts to identify water-quality problems unique to a particular watershed, pinpoint the sources of those problems, and devise a strategy for addressing them. This approach recognizes that local solutions to local problems may often be preferable to a single national solution. Voluntary watershed-pianning programs would be encouraged through a series of financial and other incentives.

Non-point-source pollution—Non-point-source (NPS) pollution accounts for half the Nation's remaining water-qualit y problems (11). S. 1114 would place stronger emphasis on mitigation and alteration in management practices to reduce the volume of polluted runoff. Mitigating NPS pollution is difficult, however, because it involves changing the land-use practices of private landowners. Runoff from agricultural lands containing, for example, nitrogen and phosphorus fertilizers, contributes a sizable percentage of nutrients and sediment to ground and surface water, but urban areas, failed septic systems, silviculture activities, cattle feedlots, and suburban development are sources of NPS pollution as well (81). S. 11 14 directs States to submit revised NPS management programs—containing specific program elements—to EPA within 30 months after the act is reauthorized.

Funding for municipal sewage treatment—The Environmental Protection Agency's (EPA's) most recent estimate of sewage-treatment requirements suggests that over $100 billion will be needed during the course of the next 20 years for State and local governments to meet the goals and mandates of the Clean Water Act (1 1). The State Revolving Loan Fund established by the CWA substantially assists communities and municipalities in

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1 To convert from gallons to liters, multiply by 3.785.

2 Secondary treatment typically means that 85 percent of solid and organic matter Is removed; advanced treatment removes more than 95 percent of pollutants and Is required when seoondary treatment is Insufficient to proteot a receiving stream and meet a State's water-quality standards.

their efforts improve water quality, but appropriations for this program are set to expire in 1994.S.1114 expands funding for wastewater treatment programs. Funds would be available for improving aging infrastructure, controlling non-point-source pollution, managing estuaries, addressing combined sewer overflows and storm-water problems, and managing animal waste.

Regulation of **toxics—EPA** currently regulates only about one-fifth of the industrial plants that dump toxic substances into rivers and lakes. Non-point sources of toxic pollutants, such as pesticides from agricultural fields and various contaminants in urban storm-water runoff, are currently unregulated (36). Toxic pollutants may have adverse effects on human and aquatic health and may remain in the ecosystem for long periods. S. 1114 calls for EPA to identify at least 20 toxic pollutants that would have to be controlled by industry through intensive pollution-prevention strategies. The bill also calls for not less than 80 percent of the volume of each pollutant listed to be reduced within 7 years and provides for the public to petition EPA to add pollutants to its list.

Wetland protection-Wetlands play a key role in preserving water quality, but the extent and nature of the authority provided by the CWAfor wetland protection promises to be a contentious issue in CWA reauthorization. The current version of S. 1114 does not address wetland protection, but an additional section on wetlands is expected to be included in the final reauthorization. The Federal Government has struggled over the past few years to reach a workable compromise with property owners, industry groups, environmentalists, and others on how and to what extent wetlands should be protected. Major wetland issues likely to be addressed in the reauthorization include clarifying the regulatory process and responsibilities of Federal agencies; clarifying the process through which States can take control of permitting; paying attention to opportunities for wetland restoration through mitigation banking; and considering whether Alaska, which has large amounts of wetlands, should receive special treatment. (See vol. 2, ch. 4, for a complete discussion of wetland issues.)

The reauthorization of the Clean Water Act comes at a critical time. The understanding of ecological processes and of the effects of human influence on ecosystems is growing. However, stresses on ecosystems are also growing. Additional data gathering and monitoring are needed to close remaining information gaps. Legislative efforts must attempt to balance human needs and ecological health.

creasingly impinge on development and use of water supplies.

Although the benefits of maintaining minimum instream flows are increasingly recognized and are gaining legal protection in a growing number of States (75), the rights to a significant amount of stream flow in the West have already been established. In Western States, rights to divert water are acquired under the prior-appropriation doctrine (i.e., first in time, first in right)(see box 5-D), and many rivers are either completely appropriated by those who got there first (senior rights holders) or are close to being so. A few are even overappropriated. The rights to water for instream uses, where protected at all, are usually very junior. This means that water for fish and wildlife has the lowest priority, and the need for it is satisfied only after the demands of senior rights holders are met. During a drought, junior and unprotected rights are most at risk, so fish and wildlife may suffer more than they would if instream water rights were better protected.

Clearly, growing competition between consumptive and environmental uses for water would be exacerbated in areas of the country that become drier as a result of climate change. If available supplies diminish and/or demand increases, existing developed supplies will have to be used more efficiently to satisfy both consumptive and environmental uses. Protecting adequate instream flows to attain multiple water-use goals, which is not easy now, could become much more difficult in the future.

Uncertain Reserved Water Rights

Rights pertaining to water for the environment are not the only “new” rights being asserted that may conflict with established uses of water.

Box 5-D-Major Doctrines for Surface Water and Groundwater

Surface Water

Riparian doctrine-Authorization to use water in a stream or other water body is based on ownership of the adjacent land. Each landowner may make reasonable use of water in the stream but must not interfere with its reasonable use by other riparian landowners. The riparian doctrine prevails in the 31 humid States east of the 100th meridian.

Prior appropriation **doctrine—Users** who demonstrate earlier use of water from a particular source acquire rights over all later users of water from the same source. When shortages occur, those first in time to divert and apply the water to beneficial use have priority. New diversions, or changes in the point of diversion or place or purpose of use, must not cause harm to existing appropriators. The prior appropriation doctrine prevails in the 19 Western States.

Groundwater

Absolute **ownership—Groundwater** belongs to the overlying landowner, with no restrictions on use and no liability for causing harm to other existing users. Texas is the sole absolute-ownership state.

Reasonable use **doctrine—Groundwater** rights are incident to land ownership. However, owners of overlying land are entitled to use groundwater only to the extent that uses are reasonable and do not interfere with other users. Most Eastern States and California subscribe to this doctrine.

Appropriation-permit systern-Groundwater rights are determined by the rule of priority, which provides that prior uses of groundwater have the best legal rights. States administer permit systems to determine the extent to which new groundwater uses will be allowed to interfere with existing uses. Most Western States employ this doctrine.

SOURCES: U.S. Army Corps of Engineers, *Volume III, Summary of Water Rights—State Laws and Administrative Procedures*, report prepared for U.S. Army, Institute for Water Resources, by Apogee Research, Inc., June 1992; and U.S. Geological Survey, *National Water Summary 1988-89—Hydrologic Events and Floods and Droughts*, Water-Supply Paper 2375 (Washington, DC: U.S. Government Printing office, 1991).

Indian reservations, National Forests, and National Parks are *reserved* lands-that is, they have been reserved or set aside from public-domain lands and, as such, carry with them authority for Federal reserved water rights (see also vol. 2, ch. 5). These rights have priority over State appropriative water rights acquired at a later date. In the case of Indian reservations, they have specifically been recognized in the Supreme Court's 1908 *Winters* decision (65), and ensuing court cases have extended the reservation doctrine to other lands.

Significantly, many Indian claims have not yet been exercised or quantified, although Indians assert large claims to both surface water and groundwater throughout the West. Because reserved rights are often senior once they are quantified, junior, non-Indian water users may have to forgo water uses in times of shortage (93). In some cases, water for settlement purposes has been purchased by the Federal Government from other water users. However, the potential for conflict between Indian and non-Indian water users is clear and could grow in areas that become drier as a result of climate change. Similarly, Federal reserved rights in National Forests and Parks have the potential for leading to disputes between States and the Federal Government if supplies decrease. Wilderness areas within Bureau of Land Management lands do not now have reserved water rights, and this has been a source of contention in most wilderness legislation before Congress.

A still-unresolved issue is whether Indians will be allowed and will choose to transfer some or all of their water off-reservation. If so, flexibility

Figure 5-3-U.S. Groundwater Overdraft

NOTE: To convert gallons to liters, multiply by 3.785.
SOURCE: H. Ingram, Udall Center for Studies in Public Policy, University of Arizona, 1993.

and economic efficiency might be enhanced, and some wealth would be transferred from non-Indians to Indians (70). The exercise of Federal reserved water rights for National Parks and Forests has proved controversial, but it is one means of providing water for such nonmarket uses as maintenance of fish and wildlife habitat (92).

Groundwater Overdraft

Groundwater overdraft is the removal of subsurface water at a rate faster than its natural recharge rate. When groundwater is pumped faster than this rate over long periods of lime, it is in effect being mined and, therefore, is nonrenewable. Overdraft is a problem in several parts of the country (fig. 5-3). It is common in the Ogallala Aquifer, for example, which is the principal source of water for farming on the Texas High Plains (see box 6-G), and to a lesser degree, in some sections of the aquifer that underlie other Plains States. Overdraft leads to successively higher water costs because pumping expenses increase as the water table is drawn down. Higher costs, in turn, can lead to adoption of innovative water-saving strategies, dryland farming, or reduced planted area. Groundwater overdraft also occurs in the southern half of California's Central Wiley, much of Florida, and parts of other States. Some regions are trying innovative plans to restore or conserve groundwater supplies (e.g., Arizona with its Phoenix-area groundwater replenishment plan).

Climate change will Meet groundwater. In some locations, it could increase recharge, but it could also lead to increased groundwater pumping in areas where surface-water supplies diminish. Mining groundwater may sometimes make economic sense (as, for example, can mining coal) but, where feasible, it should be viewed only as a temporary adaptation to climate change. To the degree that groundwater is mined, flexibility to respond to future dry spells and droughts is reduced. Overdraft may also lead to land subsidence. Temporarily increasing groundwater pumping, however, can be an effective short-term response to drought-whether it occurs under current climate conditions or during a future warmer climate.

Outmoded Institutions

Most laws and institutions guiding the allocation and use of water were established when water was essentially free and supply greatly surpassed demand. These provisions served their regions reasonably well when most new demands could be met by developing new supplies. However, new development is no longer either easy or inexpensive, and in some areas, it is practically impossible. Institutions and laws must increasingly deal with shortages and competing legitimate demands for water, many of which represent new tasks for which they were not originally designed (15). Subject to changing competitive demands and societal interests, some institutions are too rigid and inefficient to allow adequate responses to real or apparent water scarcity. Also, little has been done to educate the public about water issues, and as a result, professional knowledge of the value and scarcity of water has not been adequately disseminated.

Examples of innovative institutions are not rare, however, and institutional change is occurring. Congress, for example, passed the Central Wiley Project (CVP) Improvement Act in 1992, which explicitly recognizes the importance of instream uses for water in California's Central Valley and the need to balance competing demands for water. The Act includes provisions to: 1) guarantee that much more water will remain in streams for fish or be directed to wildlife refuges, 2) remove institutional obstacles that limit beneficial water transfers and discourage conservation, 3) raise the price of Water sold to farmers, 4) establish a fish and wildlife restoration fund (to be financed by fees on CVP water and power sales and on water transfers), and 5) place limits on the renewal of irrigation and municipal water contracts. In coming years, this law may serve as a model for similar changes in other parts of the West. Arizona's Ground-Water Management Act, with its goal of safe yield in the State's important groundwater basins, is another innovative, if imperfect, institutional change.

Nevertheless, rigid and inefficient institutions are common. Such institutions can add to the stress already on water resources by making adjustments to new situations more difficult. When water rights are unclear, for example, as they continue to be in parts of the West, reallocation of water is difficult. Agreements abound that were negotiated when either information was inadequate or future circumstances concerning supply and demand could not be foreseen. These agreements constrain the responses that water resource managers can make to short- and long-term problems, and they are often difficult to change.

For example, much water is supplied to Southern California by the Metropolitan Water District (MWD). By statute, MWD member agencies are entitled to water in proportion to their percent contribution to MWD tax revenues. Los Angeles currently contributes about 27 percent but now uses only 5 percent of its allotment because its other sources are usually adequate. San Diego, however, takes up the slack and currently uses about 30 percent of MWD supplies, although it is entitled to only 12 percent. If Los Angeles' supplies shrink during a drought, the city would be entitled to claim its MWD allotment, and San Diego, which receives about 90 percent of its water from MWD, would have to cut back (91). As San Diego grows, the potential for significant water shortages could create a critical problem during drought.

Similarly, the structure of the Colorado River Compact and related laws governing the Colorado River System make it impossible to operate this system as efficiently as possible. Problems are already apparent, given aridity, growing and shifting populations, and the fact that the Compact, negotiated in 1922 after a few unusually wet decades, allocates more water among the seven basin States than the average annual flow (26). The Colorado could be operated more efficiently (and San Diego might have an additional source of water) if, for example, interstate water transfers were legitimized. A stumbling block is that States that have water allocations through the Compact legislation and individual contractors jealously guard their existing entitlements and believe any changes in the current institutional structure could dilute their water-use rights (70).

Current stresses on water resource systems are already motivating changes in laws and institutions. The potential for climate change adds another, if currently secondary, reason to make those changes. Given the uncertain impacts of climate change on water resources, however, institutions that are flexible (i.e., those that could facilitate adaptation in a variety of different climates) and that foster an *efficient allocation* of water would be most responsive to changes caused by global warming (47). As institutions change, *equity in* water resource allocation could be promoted by providing more opportunities for the public to become involved in decisionmaking bodies. Such involvement could stimulate healthy debate about the values at stake in water resource decisions.

In many cases, promoting flexibility, efficiency, and equity will require more coordination and cooperation among the large number of Federal, State, and local water resource organizations. (Table 5-1 shows how complex the Federal water structure alone is.) River basins and watersheds are rarely managed in an integrated fashion, for example, and there are clearly opportunities for some significant increases in yield by more-efficient joint management of existing reservoir systems (63, 64). Similarly, water-quantity laws and water-quality laws are seldom coordinated. Surface water and groundwater are often managed separately. The respective responsibilities of Federal and State agencies are sometimes unclear, and Federal Government agencies that have water responsibilities do not always cooperate with one another.

Aging Urban Water Infrastructure

The current poor condition of much of the Nation's urban water infrastructure (e.g., pipes, valves, pumping stations, and storm-water drains) could affect both safety and water-supply efficiency in the future. Also, urban infrastructure needs are likely to compete for funding with other water-development needs.

In the Northeast and Midwest, deterioration of old systems is especially a problem. In 1977, for example, the Boston distribution system, due both to leaks and nonfunctioning meters, could not account for 50 percent of the water it had distributed (89). Although the American Water Works Association recommends a 67-year cycle of replacement, many of Boston's water mains are over 100 years old. More recently, the Association found an average leakage rate of about 10 percent in a study of 931 U.S. utilities.[10] Although eliminating leakage entirely is probably not practical, opportunities exist in this area for improving the efficiency of water-supply systems.

The inability of some urban storm-water drainage and treatment facilities to handle possible increases in flood discharges is a source of concern. The need for additional facilities is growing as urban areas grow. Expenditures for new construction, maintenance, and rehabilitation do not appear to be meeting current needs, and the potential for sea level rise and urbanization of undeveloped land will likely increase needs in the future. Many communities will have to invest more in storm-water drainage or face increased property damages from flooding. In-

[10] Unpublished observations, 19%?. The leakage rate in this study included water escaping from leaks and breaks, and failed meters.

Table 5-I—Federal Offices Involved in Water Resource Planning, Development, or Management

Legislative offices (U.S. Congress)
- Senate Committee on Agriculture, Nutrition and Forestry
- Senate Committee on Appropriations
- Senate Committee on Commerce, Science and Transportation
- Senate Committee on Energy and Natural Resources
- Senate Committee on Environment and Public Works
- Senate Select Committee on Indian Affairs
- House Committee on Agriculture
- House Committee on Appropriations
- House Committee on Energy and Commerce
- House Committee on Interior and Insular Affairs
- House Committee on Merchant Marine and Fisheries
- House Committee on Public Works and Transportation
- House Committee on Science, Space and Technology
- General Accounting Office
- Library of Congress
- Office of Technology Assessment

Executive off ices
- Executive Office of the President
  - Office of Environmental Policy
  - Office of Science and Technology Policy
- Department of Agriculture
  - Agricultural Research Service
  - Agricultural Stabilization and Conservation Service
  - Cooperative State Research Service
  - Economic Research Service
  - Extension Service
  - Farmers Home Administration
  - Forest Service
  - Soil Conservation Service
- Department of the Army
  - Army Corps of Engineers
- Department of Commerce
  - Economic Development Administration
  - National Bureau of Standards
  - National Marine Fisheries Service
  - National Ocean Service
  - Nationa Weather Service
- Department of Energy
  - Assistant Secretary for Conservation and Renewable Energy
  - Federal Energy Regulatory Commission
  - Federal Power Administrations
- Department of Health and Human Services
  - Agency for Toxic Substances and Disease Registry
  - National Center for Toxicological Research
  - National institute of Environmental Health Sciences
- Department of Housing and Urban Development
  - Assistant Secretary for Community Planning and Development
- Department of the Interior
  - Bureau of Indian Affairs
  - Bureau of Land Management
  - Bureau of Mines
  - Bureau of Reclamation
  - Fish and Wildlife Service
  - Geological Survey
  - Minerals Management Service
  - National Park Service
  - Office of Policy Analysis
  - Office of Surface Mining and Enforcement
- Department of Justice
  - Land and Natural Resources Division
- Department of State
  - Bureau of Oceans and international Environmental and Scientific Affairs
- Department of Transportation
- U.S. Coast Guard
- Saint Lawrence Seaway Development corporation
- Federal Highway Administration

Independent establishments and Government corporations
- Environmental Protection Agency
  - Assistant Administrator for Water
  - Assistant Administrator for Solid Waste and Emergency Response
  - Assistant Administrator for Pesticides and Toxic Substances
- Federal Emergency Management Agency
- General Services Administration
  - Public Buildings Service
- interstate Commerce Commission
- Panama Canal commission
- Small Business Administration
  - Loan Programs
  - Pollution Control Financing Program
- Tennessee Valley Authority

Quasi-officiai agencies
- Smithsonian Institution
  - Smithsonian Environmental Research Center
  - Smithsonian Tropical Research Institute

Bilateral organizations
- international Boundary and Water Commission, United States and Mexico
- international Joint Commission, United States and Canada

SOURCE: Adapted from J. Beecher and A. Laubach, *Compendium on Water Supply, Drought, and Conservation* (Columbus, OH: The National Regulatory Research Institute, 1989).

creased flooding potential in some areas of the country as a result of climate change should be cause for concern.

Most large urban areas should be able to renovate aging infrastructure through increases in service rates. Small and medium-size water systems, however, may have much greater problems. The large costs associated with renovating infrastructure, meeting Safe Drinking Water Act standards passed in 1988 (P.L. 93-523, most recently amended by P.L. 100-572), and providing additional service to growing areas are an especially heavy burden on smaller communities. Small systems typically lack adequate managerial and technical expertise and cannot benefit from economies of scale. One recent survey of infrastructure studies concluded that the gap between investment needs and available sources of financing the renovation of the water infrastructure is between $4.5 and $6.3 billion per year over the next 20 years.

EFFECTS OF CLIMATE STRESS ON NONCONSUMPTIVE USES OF WATER

Many uses of water do not deplete the total supply of water available; these are called *nonconsumptive* uses. Prominent among these are hydroelectric-power generation, powerplant cooling, waterborne transportation, and recreation, all of which climate change may seriously effect.

Hydroelectricity is a large proportion of the total electricity generated in some parts of the country. Washington State, in particular, produces 30 percent of U.S. hydroelectricity, but hydropower is also significant in such States as California and Tennessee. Such power production is sensitive to droughts and is reduced when reservoir levels are low. Reductions in hydroelectric power can usually be filled by a shift to greater use of fossil fuels, but alternative sources of electricity cost more and cause more pollution (including carbon dioxide (CO_2) emissions). The effect of drought on power generation can be considerable: during the 1988 drought, for example, hydroelectric-power generation on the Missouri River, in the Pacific Northwest, on the Ohio River, and in the Southeast was reduced between 20 and 40 percent (57).

A primarily nonconsumptive use for water is power-plant cooling.[11] Many power plants use fresh water for condenser cooling and (sometimes) emergency cooling. Heated water discharged from power plants is returned to the stream from which it was taken. Because such water contributes to thermal pollution and can have adverse impacts on aquatic life, water temperature and quality are regulated by Federal and State Governments. When water temperatures are high, power plants often must curtail power production or use cooling towers to comply with regulations. Higher water temperatures can also reduce the efficiency of many powerplant operations, and the Nuclear Regulatory Commission mandates that nuclear power plants be shutdown if a specified upper temperature limit is reached. Other water uses may be affected if additional releases from multipurpose reservoirs are needed to moderate water temperatures (45).

Power-system operations in regions such as the southeastern United States are currently affected during critically hot summers by temperature constraints. Problems can be acute when high temperatures correspond with peak power demands. Also, on some eastern rivers, power-plant water needs are, at times, so large that there may not be enough water to dissipate heat during low-flow periods (80). Power systems could become less reliable in a warmer climate, especially during the summer (45). In turn, power-production costs and consumer-electricity prices could increase.

Waterborne transportation is also affected by drought-and with considerable adverse impacts. In 1988, water in the Mississippi, Ohio, and Missouri Rivers was so low that barge traffic was

[11] Fresh water withdrawn to produce the Nation's electricity totals about 130bgd, but currently only about 4bgd are actually consumed (66).

impaired (37). On one of the worst days, for example, 130 towboats and 3,900 barges were backed up on the Mississippi at Memphis while dredges deepened a shallow stretch of the river (57). The economic consequences of the low flows were considerable: barge and towboat owners suffered economic losses, and agricultural commodities piled up in Mississippi River ports. Conversely, railroads and some Great Lakes shippers benefited. Box 5-E describes these effects in more detail.

Recreation may seem to be a less essential use for water; however, in some areas, the economic value of water-related recreation outweighs its

Box 5-E—Navigating the Mississippi Through Wet and Dry Times

Most parts of the United States have experienced droughts or floods at one time or another. The impacts of an extended drought or major flood can be costly. The case of the Mississippi River illustrates the far-reaching effects that can occur when such extreme events lead to abnormal flows on an important navigable river. Such effects could become more pronounced if climate changes.

A significant share of the Nation's cargo moves on the Mississippi River. The river is essential for the transport of major commodities, including grain, petroleum, chemicals, and coal, both within the country and as the first step in exporting these goods. According to one recent analysis (57), "more than 300 tow and barge companies operate on the Ohio, Mississippi, and Illinois river systems, and many river ports serve the barges." The barge industry "carries 60 percent of all grain exported from the United States, and 40 percent and 20 percent of all petroleum and coal, respectively, transported within the U.S." as well as transporting "45 percent of the entire midwestern grain crop." Thus, the Mississippi-based barge industry is "a key U.S. transportation industry . . . one of the nation's major conveyors of bulk commodities," with average revenues of approximately $1 billion year.

The Mississippi's ability to maintain these transportation services is intricately related to climate. Rainfall from more than 1 million square miles (2.59 million square kilometers)[1], covering 40 percent of the United States and 13 percent of Canada, runs off and drains into the 2,340-mile-long (3,770 kilometer-long)[2] Mississippi River. From western Pennsylvania to the Great Lakes to South Dakota, water makes its way to the Mississippi through rivers including the Ohio, the Illinois, and the Missouri. The amount of water that eventually flows through the Mississippi depends on precipitation, but is also affected by human land uses that alter runoff patterns, including the planting or clearing of vegetation, commercial and residential land development, paved roads and parking lots, and various agricultural practices. The Mississippi responds to precipitation patterns throughout the region, whether rainfall is unusually high or unusually low. In addition, both the low-flow conditions caused by drought and the high-flow conditions caused by large amounts of precipitation and storms, whether or not they lead to flooding, can disrupt the Mississippi's navigation systems.

The Drought of 1988

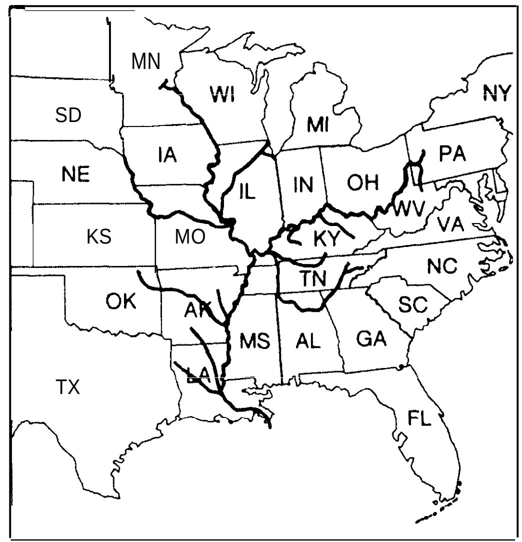
The Drought of 1988 has earned a place in popular memory for the disruptions it caused to Mississippi River navigation. The year began with light and infrequent snowfalls in much of the watershed. This resulted in much-reduced snowmelt runoff in the spring. By early April, areas around the Ohio, the upper Mississippi and the Missouri, and lower Mississippi and the Arkansas Rivers were classified as experiencing moderate to severe drought conditions, according to the Palmer Drought Severity Index (a measurement of long-term moisture conditions). Drying continued through April and May, and spread to include all regions of the Mississippi River Basin. By mid-June, 83 percent of the Mississippi River Basin was in the throes of severe drought.

[1] To convert square miles to square kilometers, multiply by *2.590.*

[2] *10* convert miles to kilometers, multiply by 1.609.

As expected, water levels in the river responded to the drought by dropping precipitously. In normal years, water flow through the river peaks in April and May. In 1988, however, water flows began to decline in April and reached record lows during May that were to continue throughout the summer. On June 8,1988, a barge-pulling tow grounded on a section of the river near St. Louis. It was the first of a series of navigational disruptions that would seriously impede barge transport on the river through late July.

Navigable Waters of the **Mississippi** River System



SOURCE: W. Reibsame, S. Chagnon, and T. Karl, *Drought and Natural Resources Management in the United States: Impacts and Implications by the* 1987-89 *Drought* (Boulder, CO: Westview Press, 1991).

Mississippi River navigation is aided by a series of locks and dams constructed and operated by the U.S. Army Corps of Engineers along the upper Mississippi as well as on much of the Missouri and Ohio Rivers. During normal years, this intricate network of water-control structures can be operated to maintain water levels and safeguard navigation during much of the year. in 1988, however, even carefully controlled and timed water releases could not prevent low water levels. Fully loaded barges require minimum water levels of 9 feet (2.7 meters)[3] to operate safely. Not only does water at this level provide sufficient clearance to keep the barge from hitting the bottom, but it also generally ensures that the water is moving fast enough to forestall the formation of shoals, sand bars that form in shallow sections of the river and impair navigation.

The first action managers generally take when water levels drop too low is to start dredging the blocked areas. Constant work by several dredges for several days can often dear the channel enough to keep it open. A second strategy is to limit the number and weight of the barges pulled by a towboat so the tow is more maneuverable and the lightly loaded barges are less likely to hit bottom. A third strategy is to release more water from upstream dams, although this can interfere with other water uses at the upstream locations (including hydropower generation, recreation, and agricultural, industrial, and municipal water supplies). In the event of severe disruptions, alternate navigation routes or modes of transportation may have to be found.

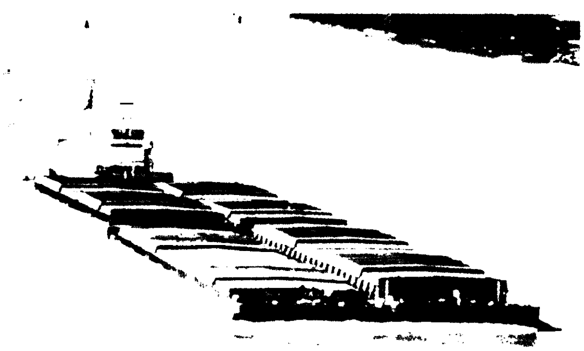
Costly barge backups

In 1986, managers drew on ail of these strategies and more. Following the June 8 grounding in St. Louis, the Corps dredged that section of the Mississippi and limited traffic to barges that drafted no more than 6 feet. Despite the Corps' efforts, water levels continued to drop. By June 15, water levels in that reach dipped to the lowest levels measured since 1872, when record keeping first began. In addition, water levels on a nearby stretch of the Ohio River dropped below 8 feet, with extensive shoaling. The Corps dosed a stretch of the Ohio for dredging from June 14 through 17. Over the next several weeks, the Mississippi and Ohio rivers were periodically dosed for dredging in locations that included Greenville, MS, Mound City, IL, and Memphis, TN. Even when the river

3 To convert feet to meters, multiply by 0.305.

(Continued on next page)

Box 5-E-Navigating the Mississippi Through Wet and Dry Times-(Continued)



U.S. ARMY CORPS OF ENGINEERS

A barge and 'towboat' on the Mississippi River. Low flows during the 1988 drought stranded thousands of barges at Memphis and other river ports. The 1993 flooding along the Mississippi and its tributaries stranded more than 2,000 barges, costing the barge industry more than $3 million per day.

remained open, river traffic and loads were reduced. By early July, river traffic was down by one-fifth, and toads totaling 15,000 tons (13.6 million kilograms)[4] of commodities had been halted.

Some barge traffic was diverted to the Tennessee-Tombigbee Waterway, a river system built and operated by the Corps that parallels the southern half of the Mississippi. The Tennessee is not usually the favored southward route because it is slower and less direct than the Mississippi, but it was able to handle more than 2.1 million tons of cargo above normal levels to relieve some of the Mississippi barge backup. As the extent of the disruption became apparent, some grain shipments were shifted to alternate ports and routes on the Great Lakes instead of the Mississippi, further absorbing some of the barge backups and storage overflows in the ports on the Mississippi.

Repercussions from the interruption in navigation were widespread. By the time of the dosing of the Ohio on June 14,700 barges were backed up at Mound City, a major grain port. With the barges not running and no empty barges arriving, grain piled up at the port. Within days, the port had to find storage space for 200,000 bushels (7,000 cubic meters)[5] of corn, and more than $1 million worth was simply stored on aty streets because there was no more room in the elevators. Thus, even farmers who managed to harvest crops despite the drought (and could potentially earn higher prices due to the lower supplies) faced the risk that their grain would spoil while awaiting shipment. Similar pileups occurred elsewhere. By June 17,700 barges were trapped in Greenville. By the 19th, 3,900 barges were stranded in Memphis. Barge traffic was sporadic through late June; in early July, another 2,000 barges were held up in Memphis.

International implications

Attempts to combat low water levels and maintain navigation even led to international controversy. It is technically feasible to increase the flow of the Mississippi River by diverting water into it from Lake Michigan through the Illinois River channel. At one point during deliberations over how to respond to the drought, the governor of Illinois proposed to triple the normal water releases from the Lake for a limited time to help restore Mississippi River levels. The increased diversion was expected to raise Mississippi levels by 1 foot at St. Louis and around 6 inches (15 centimeters)[6] at Memphis, while lowering the level of Lake Michigan by only 1 or2 inches. This proposal caused considerable controversy when introduced, however, because it ignored the history of controversy over water diversions, and because at the time of the proposal, Lake Superior water levels were well below average even though they had been at record high levels just 2 years before. Governors of four Great Lakes States threatened court action, and the Canadian ambassador delivered a formal protest to the U.S. State

4 To convert tons to kilograms, multiply by 907.

5 To convert bushels to cubic meters, multiply by 0.035.

6 To convert inches to centimers, multiply by 2.540.

Department. Residents on both sides of the Great Lakes considered the levels of the Lakes-already low due to the drought-of fundamental importance and declared that the levels should not be artificially altered for any reason. Sufficiently low lake levels could, among other things, disrupt the operation of locks, thus affecting shipping activities and the production of hydroelectric power at Niagara and on the St. Lawrence River. In the end, the Illinois governor backed off the proposal, and no water was diverted.

Winners and losers

The economic costs due to less-efficient barge transport may have reached $1 billion. Farmers, agricultural chemical manufacturers, and coal and oil companies found it more costly to ship products as barge shipping prices quickly rose from $9 to $15 per ton. Barge shipping was reduced 20 percent, costing the industry perhaps $200 million. Other losers included the consumers of shipped commodities, particularity utilities forced to pay higher prices for coal. in addition, the drought ied to a 25 percent drop in hydropower production on the river and a 15 percent decline in recreational use, and low water levels allowed sait water from the mouth of the Mississippi to travel 105 miles inland, damaging wetlands along the river.

Despite considerable turmoil and costly losses to shippers and the barge industry, there were others who benefited from the drought, partly offsetting the overall costs. Shippers on the Tennessee-Tombigbee and the Great Lakes received a considerable boost in business, and showed gains in economic competitiveness due to the greater reliability of their routes. The Illinois international Port at Chicago shipped nearly $2 million worth of grain that would otherwise have been shipped through Mississippi River ports, generating an income for the port of $0.5 million. On the other side of the Lakes, shipping traffic on the St. Lawrence Seaway rose by 7 percent during the summer months.

Perhaps the biggest winner was the Illinois Central Railroad (iCRR), a north-south system running from Chicago to New Orleans. Because its route is roughly parallel to the Illinois-Mississippi River system, the railroad has iong been a competitor with the barge industry. In 1988, the going rate for shipping by rail was $8 to $12 per ton, which put the ICRR at a considerable disadvantage in competing for cargo with the barge industry, which generally charged around $5 per ton. When barge prices increased to $14 to $15 per ton due to the backups, however, the ICRR was well-situated to compete.

The Flood of 1993

The Drought of 1988 illustrates the powerful role that climate plays in maintaining the navigational services that many have come to expect from the Mississippi. in times of drought, the iow water levels that caused shoaling and grounded tows in 1988 can also affect wintertime navigation because the river freezes up more quickly and extensively in shallow areas. Conversely, during times of above-average precipitation, floods can be disruptive as some stretches of the river become nonnavigable during high flow. Flooding along the Upper Mississippi and many of its tributaries reached levels in June and July 1993 not seen in many decades. A 500-mile stretch of the upper Mississippi, from St. Paui to St. Louis, was shut to ail commercial traffic, leaving thousands of barges stranded. Water levels did not return to normal for more than a month, wit h costly effects on grain shipments f rom Iowa, Missouri, Illinois, Minnesota, and Wisconsin. Cargoes heading north (e.g., rubber, sugar, and metal from overseas) were aiso stranded. The flooding caused many small towns to be evacuated and darnaged thousands of homes and businesses. Crop losses have been estimated to be between $5 and $10 billion.

Considerable uncertainty surrounds predictions of climate change in the Mississippi River Basin. Nevertheless, both the 1988 drought and the 1993 flooding could be harbingers of the challenges ahead for the barge industry-and for others who iive near and/or depend on the Mississippi.

SOURCES: This box is drawn largely from W. Riebsame, S. Changnon, Jr., and T Karl, *Drought and Natural Resources Management in the United States: Impacts and Implications of the 1987-89 Drought* **(Boulder, CO: Westview Press, 1891), pp. 43-112. Supplemental material came from W. Koellner, "Climate Variability and the Mississippi River Navigation** *System,"* **in:** *Societal* **Responses to** *Regional Climate Change: Forecasting by Analogy,* **M.H. Glantz (cd.) (Boulder, CO: Westview Press, 19S8), pp. 243278; Levels Reference Study Board, "Final Report of CCC GCM 2 X CO_2 Hydrological Impacts on the Great Lakes" (Hanover, NH: Levels Reference Study Board, December 1991); and Reuters Ltd., "Midwest Levees Straining: Mississippi River Continues to Rise,"** *Washington Post,* **July 8, 1993, p. A3.**

Recreation is an important nonconsumptive use of water, and in many areas, one of its highest-valued uses.

use for irrigation or other purposes. Low lake levels may leave recreational boating docks high and dry and may affect shoreline property values. Low flow conditions in mountain streams affect white-water rafting, fishing, and other types of water-related recreation.

Current allocation problems on the Missouri River illustrate the value of' water-related recreation, the considerable conflicts that can develop between instream and offstream uses for water, and the conflicts that can arise among different instream purposes. The Upper Missouri River Reservoir System (UMRRS) is operated by the Army Corps of Engineers for a variety of purposes, chief of which are irrigation, navigation, and flood control. The Corps, however, is under pressure from upstream States to give greater consideration to recreation and fish and wildlife interests in operating the System. When priority is given to navigation during drought periods, boating facilities in upstream lakes (for example, Fort Peck Lake in 1991) can be left high and dry, and fish habitat can suffer. Upper Missouri River States (Montana and North and South Dakota) have decried this situation because, as the Corps notes, the recreational value of the UMRRS, at $65 million annually, is now roughly four times the economic value of navigation (2). Upper Missouri River States, which would like to seethe operating rules changed to better reflect current economic realities, are now pitted against Lower Missouri River States, which want the rules to remain the same to protect the hydropower and navigation purposes of the System. Similar conflicts can be found in many places in the United States, and such conflicts are inevitably more heated during drought.

ADAPTING WATER RESOURCE SYSTEMS TO CLIMATE AND OTHER CHANGES

Water resource planning is a complex political, economic, sociological, scientific, and technological endeavor (60). Therefore, adaptation to change, whether climate or otherwise, will rarely be straightforward. Adaptation measures must accomplish several objectives if they are to be successful. They must address the sources of stress, whether due to short-term or long-term imbalances between supply and demand, threats to water quality, high costs, or other factors. They must be politically and administratively feasible--water resource systems exist in complex institutional environments, and changes must be capable of operating in conjunction with existing laws, agencies, and regulations. (Box 5-F describes some important water responsibilities of key Federal agencies.) Changes should enhance the flexibility and robustness of water resource systems because the timing and magnitude of regional climatic events may change in as yet undetermined ways. And, finally, costs and benefits arising from institutional changes must be perceived as equitable if they are to be supported and remain successful in the long run (23).

Adaptation measures in the near future are likely to be taken in response mainly to problems more pressing than climate change, but many of these measures could also address climate change concerns. Consideration of the potential for climate change in water resource planning could sometimes make a difference in the choice among types and timing of new policies or projects. Hence, even without sufficient regional da@ it

Box 5-F-important Water-Related Responsibilities of Key Federal Agencies

The Federal Government is *involved* in virtually every aspect of water resource planning, management, regulation, and development. In all, at least 35 units-including agencies, bureaus, and services-within 10 different Federal departments, as well as 7 independent agencies and several bilateral organizations, currently exercise some responsibility for water programs and projects(4). These programs are governed by more than 200 Federal rules, regulations, and laws. Some 7 House committees and 13 subcommittees, plus 6 Senate committees and 10 subcommittees exercise responsibility over distinct aspects of water resource development and management (13) (see table 5-3). Responsibilities of some Federal agencies with important water-related programs are listed below.

Department of Agriculture (USDA)

Soil Conservation service (SCS)—Helps farmers develop soil and water conservation plans and arrange for cost-share funding for implementation of conservation practices. In cooperation with other agencies, offers advice to farmers on pesticide and fertilizer use and land management. Several programs promote water quality, including the Conservation Reserve Program, the wetlands Reserve Program, the Agricultural Water Quality Protection Program, and the Small Watershed Program.

Department of the Army (DOA)

Army Corps of Engineers (the Corps)-In budgetary terms, the most important Federal water resources development agency. Responsible for planning, design, construction, operation, and maintenance of projects for flood control and floodplain management, water supply, navigation, hydroelectric power, shoreline protection, recreation, fish and wildlife management, and environmental enhancement. Reservoirs managed by the Corps, which include most of the largest reservoirs in the United States, hold about 65 percent of the Nation's stored surface water. The Corps has undertaken several climate-change-related studies, including analysis of decision making about water resources given the uncertainty of climate change.

Department of Commerce (DOC)

National Oceanic and Atmospheric Administration (NOAA)—Within the context of its coastal zone and fisheries management responsibilities, concerned with watershed management and non-point-source pollution; Office of Hydrology provides streamflow and flood-forecasting services.

Department of Energy (DOE)

Federal Energy Regulatory Commission (FERC)—Issues licenses for nonfederal hydropower projects; considers measures to preserve environmental quality, protect fish and wildlife, and maintain scenic values, as well as those to maintain dam safety, flood control, and recreational opportunities.

Federal Power Administrations (FPAs)—Five Federal power administrations market hydroelectric power, including Bonneville, Southeastern, Alaska, Southwestern, and Western Area Power Administrations.

Department of the Interior (DOI)

Bureau of Reclamation (the Bureau)—Supplies municipal water to 25 million people in 17 western States, provides irrigation water for 10 million acres (4.05 million hectares)[1] of western farmland, and operates 52 hydroelectric facilities that generate 46 billion kilowatt-hours of electricity annually (making the Bureau the Nation's 1 lth largest electric utility). The facilities operated by the Bureau provide local flood control, fish and wildlife

[1] To convert acres to hectares, multiply by 0.405.

(Continued on next page)

Box 5-F–important Water-Related Responsibilities of Key Federal Agencies=(Continued)

enhancement and recreation.The Bureau has established the Global Climate Change Response Program to study the potential impacts of global climate change on water resources in the 17 Western States.

Geological Survey (USGS)—Conducts assessments of the quality, quantity, and use of the Nation's water resources; produces annual state-by-state summaries on special topics (e.g., floods and droughts). USGS has initiated a Global Change Hydrology Program, the objectives of which include improving methods for estimating the sensitivity of water resource systems to climate variability and change across the range of environmental conditions existing in the United States and improving understanding of the effects of climate change on the hydrology of watersheds.

Fish and Wildlife Service (FWS)—Lead Federal agency for conservation of fish and wildlife and their habitats; responsible for endangered species, freshwater and anadromous fisheries, certain marine mammals, and migratory birds. Manages 700 national wildlife refuges; assesses environmental impact of hydroelectric dams, stream channelization, and dredge and fill operations. An FWS goal is to assess the significance of global climate change on fish and wildlife.

Environmental Protection Agency (EPA)

Plays a major role regulating water quality by issuing permits for discharge of pollutants into navigable waters, developing criteria that enable States to set water-quality standards, administering State grant programs to subsidize costs of building sewage treatment plants, setting national drinking-water standards, and cooperating with the Corps to issue permits for the dredging and filling of wetlands, for example. Works wfth States to promote watershed management and reduction in non-point-source pollution. EPA is the lead agency for the National Estuary Program.

Federal Emergency Management Agency (FEMA)

Undertakes hazard mitigation, preparedness planning, relief operations, and recovery assistance for floods and droughts and other natural and humanmade disasters; has undertaken a study of the possible impact of sea level rise on the National Flood Insurance Program.

Tennessee Valley Authority (TVA)

Government-owned corporation that conducts a unified program for advancing resource development and economic growth in the Tennessee River Valley region. TVA manages the 50 dams and reservoirs that makeup the TVA system. Its activities include flood control, navigation development, and hydroelectric power production. TVA is studying the sensitivity of its reservoir and power-supply systems to extreme weather.

may be important to take some actions soon or in the relatively near future to avoid climate-change-related regrets later. Projects that require long lead times for construction or implementation may deserve special attention with respect to climate change. In some instances, it may be advantageous to avoid taking certain actions (e.g., building in flood-prone areas) until better information about climate change, future water demand,[12] and other factors is available. A few measures might be motivated solely in anticipation of a changing climate, but most are likely to be taken primarily in response to other stresses.

[12] Projecting future demand has been exceptionally difficult, and studies have shown that most forecasts made in the 196@ and 1970s of current water use have been substantially in error (60). Projecting demand is complicated because the future regulatory framework for water resource management and the types of adaptation that will be politically, economically, socially, and environmentally feasible are uncertain. The importance of climate change in water resource planning relative to these other sources of uncertainty is difficult to gauge.

Potential adaptation measures are considered in several categories below: demand management, water reallocation, and supply management all deal with using existing supplies more efficiently. Supply augmentation increases the amount of water available by developing new sources. Flood and drought contingency planning introduces more flexibility during emergency situations and helps to mitigate damages.

Demand Management and Water Reallocation

Until relatively recently, the preferred approach to satisfying the water needs of growing communities has been to develop untapped supplies. As new water-supply sources have become less accessible, and as developing them has become more expensive and less acceptable environmentally, managing demand and enabling voluntary water reallocation have taken on increasing importance. Demand management and water marketing could be very important in coping with climate change, both because they promote efficiency and because they enable a considerable amount of flexibility in water resource management.

The objective of demand management is to use water more efficiently, and many regulatory and water-pricing options can be used to promote the development and use of more-efficient water-use technologies and practices. Demand-management options include such measures as: 1) modifying rate structures, 2) reducing landscape water use, 3) modifying plumbing and irrigation systems, 4) conducting educational programs, and 5) metering. Temporary measures can provide great flexibility in relieving stress during droughts. Efficiency gains from permanent measures could offset or postpone the building of large and costly structures that might otherwise be needed to deal with climate change and other factors leading to increased demand.

Demand-management measures are also important because they often have short payback periods and lead to reduced capital and operating costs for water supply and wastewater treatment facilities. Water saved through demand management can be made available to protect wetlands and fish and wildlife habitats, and reduced wastewater and drainage flows can yield additional environmental advantages.

The important question is not whether demand-management practices should be pursued, but how conserved water will be used. If the water is to be used entirely to meet the needs of unlimited urban growth, for example, water-use problems are likely to recur at a later date. Flexibility can be maintained by reserving some conserved water for instream purposes.

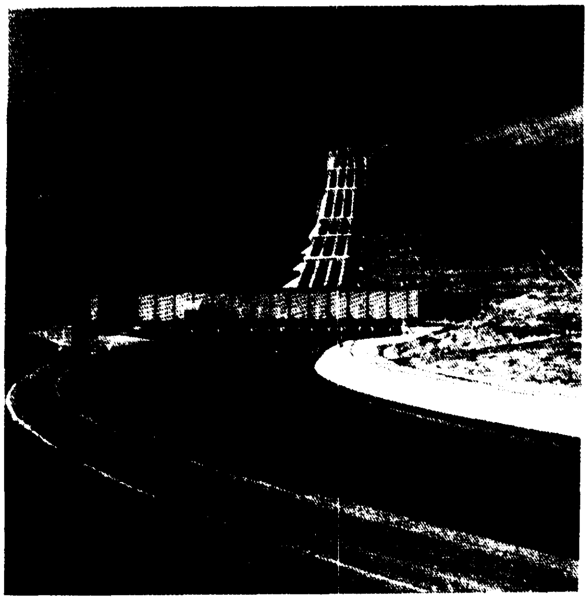
Likewise, the primary objective of enabling water reallocation is to promote more-efficient water use. Water reallocation is facilitated by allowing water to be marketed, that is, transferred from willing sellers to willing buyers. Water marketing is an important means of transferring accurate price signals regarding the value of water and is therefore closely linked to demand management (65). If owners of inexpensive water are allowed to sell it at higher market prices, they will have an incentive to conserve, and those willing to pay higher prices for water are unlikely to do so only to use it inefficiently.

Water Reallocation Through *Marketing* and Other Transfers

Water has very different costs depending on its use and typically has the lowest value in those sectors that consume the most of it. The disparity between the relatively high prices paid by urban entities and the low prices paid by agricultural users suggests that opportunities exist to use markets to allow more-efficient allocation of water.

However, the lack of institutional and legal mechanisms for facilitating markets has so far limited their development. Other types of transfer arrangements that may or may not be considered ‘‘marketing can also be effective. Most of the water trades and transfers occurring to date have

STATE OF CALIFORNIA, DEPARTMENT OF WATER RESOURCES



The California State Water Project currently transfers about 2.5 million acre-feet (3 billion cubic meters) of water annually from northern to southern California. Together with California's Central Valley Project, it comprises one of the most massive water-redistribution systems in the world. Shown is the California Aqueduct and the Ira J. Chrisman Wind Gap Pumping Plant near Bakersfield, California.

involved the transfer of water from rural agricultural uses to municipal or industrial uses; some trades, however, have been made between agricultural regions.

Properly implemented, water markets and transfers can serve to reallocate: water quickly and efficiently under current climatic conditions. Marketing arrangements can vary from "permanent' sales[13] of water to short-term, seasonal, or dry-year agreements. Box 5-G illustrates a permanent transfer in which California's Metropolitan Water District agreed to improve the Imperial Irrigation District's canal system in exchange for the water saved by these improvements. Box 5-H illustrates an innovative dry-year agreement, also in California, designed to meet demand during droughts.

Each of the types of reallocation agreements described in boxes 5-G and 5-H could also serve to provide more-efficient and flexible use of water in the event the number, duration, or intensity of extreme events increases. Indeed, severe drought conditions in the West between 1987 and 1992 may offer a glimpse of what problems a future, drier region would encounter and of some of the measures that might be taken in response. Approaches similar to California's Drought Water Bank are likely to be useful in other regions and could eventually become permanent institutions. Such sales of water to higher-value uses would ensure that as much economic productivity is maintained in a region as possible.

An additional characteristic of water markets is that they do not inherently require long lead times to establish, such as are required of new dams. California's Drought Water Bank, for example, although not without problems and not a full-fledged market, was implemented in several months. Water markets and market-like transfers may allow society to delay or avoid more-costly or less-flexible adaptation options.

Despite the advantages of water reallocation, the possibility that water transfers could adversely affect parties not directly involved in them has left some people wary. Several issues that often arise are: What review process or standard should be used to balance the benefits to farmers from water trades against the secondary economic effects on the local community? What are the obstacles facing a sale or trade when farmers receive their water from an irrigation district or pursuant to a contract with a Federal water project? How will transactions cope with surface-water return flows and groundwater recharge? Who protects freshwater fisheries, recreational white water, and other ecologic and aesthetic values of rivers (65)? Some States have taken steps to modify their water codes to address

[13] Permanent, that is, from the point of view of the entity selling the water. Such a transfer would not necessarily prohibit the water from being resold.

Box 5-G-Permanent Transfer: Conserving Water in California's Imperial Valley

Southern California has four major water sources, and all are threatened to some degree. increasingly strict water-quality regulations threaten the use of some local water supplies (9O percent of which is groundwater); importation of Colorado River supplies is being scaled back as Arizona's Central Arizona Project comes on line; litigation is forcing Los Angeles to reduce importation of water from the Owens Valley and Mono Lake Basin; and in 1982, the future of obtaining additional water from northern California was clouded as voters rejected the Peripheral Canal across the Sacramento-San Joaquin Delta (29).

Southern California's population is expanding even as its traditional water supplies contract. Los Angeles and San Diego are two of the country's IO fastest-growing counties (44), and the region's population of 14 million could grow to 18 million by the year 2010 (29). Because population growth is expected to outstrip recent declines in per capita water use, Southern California could soon face severe water shortages. As part of its efforts to avoid such shortages, the Metropolitan Water District (MWD) has been active in pursuing opportunities for water transfers. One of the largest transfers pursued by MWD is a conservation agreement with the Imperial irrigation District (iID).The IID diverts 2.9 million acre feet per year (af/year)[1] from the Colorado River and is California's largest water user, but in the early 1980's, IID was criticized by State Government and the courts for wasting water. The California Department of Water Resources was able to identify operational and physical improvements in IID's water-distribution system that could save an estimated 438,000 af of water per year (54).

in 1988, after years of intense and sometimes acrimonious negotiation, MWD and IID reached an agreement in which MWD agreed to fund IID conservation projects in return for an estimated 100,000 af of saved water per year (54). MWD is to contribute money directly to the IID Conservation Fund, which is controlled entirely by IID. Projects must be approved by a program coordinating committee appointed by MWD and IID. Projects will include lining canals; installing gates and automation equipment; constructing spill-interceptor canals, regulatory reservoirs, and tail-water recovery systems; and other monitoring and management measures. The Program Coordinating Committee is responsible for seeing that ail projects are operating within 5 years of the effective date of the agreement (54).

in addition to construction costs for the original projects, MWD is to pay for any conservation structures that need to be replaced during the term of the agreement. MWD is also to pay ongoing direct annual costs of nonstructural programs, such as those involving monitoring and management, and $23 million for indirect costs, including costs of environmental damage, lost income from hydroelectric generation, public-information programs, and litigation on related issues. in return, MWD expects to receive approximately 100,000 af of conserved water per year for 35 years at an average total cost of approximately $128/af (Pius $20/af for pumping (54)).

Many legal and institutional obstacles had to be overcome to conclude the transfer agreement. Controversy surrounded the issue of whether or not IID was legally able to sell conserved water; some argued that under anti-waste provisions of California State iaw, the conserved water should automatically revert to holders of the next priorities for Colorado River water. The issue was eventually sidestepped by referring to the agreement as a "water salvage arrangement" rather t han a sale, but t he issue may still be raised in future litigation (54). Agreements also had to be reached with the Coachella and Paio Verde irrigation districts to ensure that MWD would be allowed to receive the conserved water because these irrigation districts' Colorado River priorities are lower than IID's but higher than MWD's.

Despite the numerous institutional obstacles and other difficulties, the MWD-IID transfer arrangement is seen as a success by both parties. MWD is satisfied to receive additional water supplies at a reasonable price, and IID has been pleased to receive an improved distribution system at MWD's expense (54).

[1] 3.6 billion cubic meters/year; to convert from acre-feet to cubic meters, multiply by 1,234.

Box 5-H—A Drought-Year Option: California's Drought Water Bank

In December 1990, California was in the midst of its fourth consecutive year of drought. Reservoir storage was only 32 percent of capacity, statewide precipitation averaged only 28 percent of normal for the 1990-1991 water year, and most snowpacks were less than 30 percent of normal. Both the State Water Project (SWP) and the Central Valley Project (which, respectively, account for about 7 and 22 percent of California's water supplies) were forced to cut back sharply in water deliveries. SWP, for example, announced cutbacks of 90 percent to municipal users and was forced to suspend all deliveries to agricultural users. The State Department of Water Resources (DWR) was predicting that the drought would likely continue into the new year, and the State Water Resources Control Board had prepared a list of draconian regulatory measures that might need to be taken to mitigate the crisis (30).

On February 15,1991, with no expectation of sufficient rain for the season, Governor Pete Wilson announced a four-point plan to deal with the drought. As part of the plan, he established the Drought Water Bank. Intended to operate only during the emergency, its charge was to purchase water from willing sellers and sell it to entities with critical needs (7). Bank members could be corporations, mutual water companies, or public agencies (other than DWR) that had responsibility to supply water for agricultural, municipal and industrial, or fish and wildlife needs. Members were required to meet rigorous criteria (e.g., they must have already made maximum use of all available supplies) to qualify as having critical needs. Sellers were assured that transfers would be considered a reasonable beneficial use of water, not constitute evidence of waste and not be evidence of surplus water beyond the terms of the agreement. The Bank was not intended as a precedent for California water policy or law, but was undertaken solely to help cope with 1991 drought conditions.

Water for the Bank was acquired through land fallowing (i.e., not planting or irrigating a crop), using groundwater instead of surface water, and transferring water stored in local reservoirs. Most of the 351 contracts negotiated were for fallowing land, but the largest acquisition came from transferring stored water. The Bank initially paid sellers $125/per acre-foot (af)[1] but after rainfall in March exceeded expectations, estimates of water needs were lowered, and a few sellers were offered $30/af. The bank, in turn, sold the water for $175/af (sometimes

[1] To convert acre-feet to cubic meters, mutiply by 1,234.

these issues, but State water codes are not uniform and not equally conducive to transfers.

Water transfers have a controversial history to overcome—the earliest often took place without adequate consideration for equity, regional economics, the environment, or areas of origin. Water transfers have sometimes been referred to as ''water grabs" because gains to the receiving water users have often come at the expense of a loss of water security and opportunity for water users in the area of origin. The classic example is the Owens Wiley of eastern California, where early this century agents for the City of Los Angeles made several disguised purchases of land for the purpose of diverting the associated water hundreds of miles to the south. The economic and environmental impact on Owens Valley was devastating, and the Valley has never recovered (53). Box 6-D describes how water transfers have hastened the decline of farmingin Colorado.

Transfers do not necessarily result in losses, however, and the transfers described in boxes 5-G and 5-H contain features that make them beneficial to buyers and sellers, and they have generally been successful in increasing available supplies without significantly endangering "third-party" interests. As experience is gained with transfer mechanisms and States ensure protection of third-party interests, some current concerns should be allayed (50).

Promotion of interstate, as well as intrastate, transfers could help make management of water the amount paid to sellers, contract administration costs, and conveyance losses. Buyers also paid the cost of conveying water from the Sacramento-San Joaquin Delta to their service area

Surprisingly, the Bank was able to purchase about 820,000 af of water in about 45 days. Eventually, about 400,000 af were disbursed to Bank members for critical needs, and 260,000 af were carried over into 1992 for SWP. Some of the excess water acquired was lost in conveyance or was used to maintain water-quality standards in the Delta The rest was used to replenish carry-overcapacity as insurance against the possibiiitythat the drought could continue into 1992.

in ail, particularly given the lack of experience California had with water trading and the crisis nature of the program, the Water Bank was considered very effective in reallocating water. Many were concerned, however, that water trading would have adverse impacts on local economies and on the environment. indeed, there were some losers; however, the adverse economic impacts were minimal, and overall, the Bank created substantial gains for California's agriculture and economy. Fallowed iand accounted for only about 10 percent of planted area in major counties, and even where fallowing represented the largest portion of decline in planted area, the overall net effect on county personal income and total employment was relatively small. The jobs that were lost in exporting regions were more than offset by the jobs gained in importing agricultural regions. Estimated income gains in importing agricultural regions ($45 million) were more than three times greater than estimated income losses in exporting regions ($13 million) (30). Estimated net benefits in urban areas were OVer $90 million, even without accounting for the value of increased carry-over storage.

Many people believe that the Bank has just scratched the surface of its potential for facilitating transfers. Some, however, are concerned with this success. Environmentaiists worry that there is currently no mechanism for allocating water to fish and wildlife. Local officials remain concerned about the possible impact an expanded water bank could have on their tax base and on social-services budgets. Rural communities fear that banking could accelerate either their demise or their development into suburban areas. Considerable disagreement exists about whether the Water Bank should be permanent or implemented onty during emergencies. Neither rural areas nor environmentalists want urban areas to use the Water Bank as an excuse for forgoing water development, conservation, or reclamation programs. Minimizing future Bank impacts on local economies may be possible by, among other things, ensuring a wide regional distribution of fallowed area, increasing reliance on groundwater exchanges, and switching to less-water-intensive crops (30).

resources more flexible and efficient, especially where infrastructure for transferring the water already exists. Such transfers, for example, could be useful in the Colorado River Basin. Without some vehicle for transmitting price signals across State borders, low-value irrigation uses in the Upper Basin States have the potential to displace high-value urban uses in the Lower Basin, where water may have 10 times the value. Several proposals for interstate marketing of Colorado River water have already been made, including recent ones motivated by the California drought that began in 1986 (9). Increased aridity in the Southwest, possibly as a result of climate change, will likely focus additional attention on interstate transfers in the future.

Demand Management Through *Pricing* Reform

Water conservation could be promoted not only by allowing markets to provide accurate price signals, but by changing some pricing practices that lead to inefficient water use. Perhaps one of the biggest obstacles to more-efficient water use is that Americans are frequently charged much less for water than it costs to supply it. Water is usually treated as a free resource in the sense that no charge is imposed for withdrawing water from a surface or underground source. Users may pay for storing water and for transporting it to where it is used (although sometimes at highly subsidized rates), and also for treatment of the water and disposal of the return flows, but there is rarely any charge to reflect the value of water for a given use, that is, the *opportunity costs* of putting water to one use at the expense of another (22). As a result, few people have incentives to use water efficiently. Policies that underprice water have been much criticized for not promoting efficient use in urban areas and on lands irrigated with federally supplied water (91).

Urban pricing structures often include such economically inefficient practices as: 1) using average-cost rather than marginal-cost pricing,[14] 2) using decreasing block rates—in which the cost of the last units consumed is lower than the cost of initial blocks, 3) recouping a significant fraction of facility costs through property taxes rather than through charges based on water use, 4) failing to meter individual consumers, and 5) failing to use seasonal pricing if marginal cost varies by season. These common practices provide inappropriate price signals to consumers and lead to overuse of water. They also result in overinvestment in water-supply facilities relative to investment in other methods of providing or conserving water and relative to expenditures on other goods and services (92).

The large Federal subsidies received by farmers who contract for water with the Bureau of Reclamation (the Bureau) likewise lead to overuse of water. The Bureau, which was established in 1902 with the principal goal of assisting the development of family farms in the arid West, now supplies about 30 million af of water per year in the 17 Western States—about 25 percent of western irrigation. The cost-recovery provisions in reclamation law provide Federal subsidies for irrigation, and these have grown substantially over time. Subsidies on irrigation capital costs, such as interest-free repayment of capital, have reached levels of over 90 percent, and historically, program-wide subsidies of irrigation capital costs have been estimated at 85 percent (91).

Interest-free repayment for irrigation appears to be an anachronism in the 1990s. The West has been settled, and States now have their own water resource programs. Where farmers must pay prices that reflect the market value of water, there will be greater motivation to use water more efficiently. However, small price increases will likely do little to motivate changes in use if the gap between the price paid and the market price remains large.

Improvhg Conservation Practices

Many technical and regulatory possibilities exist for using water more efficiently (see table 5-2). Additional water-conservation research could also help realize new savings opportunities and bring down costs of existing ones.

Conservation is likely to have more potential for reducing water use in irrigated agriculture than in cities, given that 85 percent of all water consumed is for irrigation. Moreover, in the agricultural sector in Western States, traditional water law has been a powerful disincentive for practicing conservation. For example, where the prior-appropriation doctrine is practiced, farmers must use the water they have appropriated or they face losing it. Savings of agricultural water can be obtained by such practices as lining canals, recovering tail water at the end of irrigated fields, and better scheduling of water deliveries. Savings might also be made possible by developing more water-efficient crop varieties or crops with a higher tolerance for salt (18).

The High Plains of Texas illustrate the potential for conservation in agriculture (see box 6-G for details). Here, the high costs of pumping groundwater for irrigation motivated a substantial public education program and widespread use of water-saving technologies. Where irrigation costs are low, as in much of California's Central Wiley, there is little incentive to spend money on water conservation.

Significant savings are available through urban conservation efforts as well, and the rate of

[14] *Marginal-cost* pricing is the cost of providing the last increment of water. When the average cost is less than the marginal cost, as in many western cities, pricing at the average cost encourages excess use of water.

demand growth in this sector is much higher than it is for agriculture. Municipal water-conservation programs are in operation in cities from Boston to San Diego, yet in most parts of the country, a strong water-conservation ethic has not developed. Nevertheless, examples of innovative municipal programs abound, and many of these programs could be applied more broadly. One innovative and flexible program is the Conservation Credits Program of Southern California's MWD. Under the terms of this program, MWD, a wholesale water corporation, pays $ 154/af (less than its cost for developing other new supplies) for demonstrable water savings from qualifying local-agency conservation programs, with an upper limit of one-half of the program cost, To qualify, local-agency projects must result in decreased demand for MWD imported water, be technically sound, and have local support (44).

Many of the approved conservation projects are aimed at implementing the 16 Best Management Practices (BMPs) proposed by MWD and other urban water districts.[15] These include retrofitting showerheads and toilets; conducting home-water audits, distribution-system audits, and large-landscape-water audits; finding leaks in distribution systems; instituting landscaping requirements; and several other practices expected to save substantial amounts of water (44). MWD's goal is to conserve 830,000 af/year by the year 2010.[16] If conservation programs are perceived as equitable and fair, people are more likely to support them.

As important as conservation can be, it does have its limits. In areas where comprehensive conservation has begun, demand management may not yield large additional savings (47). To the extent that conservation is successful and growth in demand continues (e.g., through increases in population), long-term water-management flexibility through decreased water use will be harder to achieve. The limits of

Table 5-2—Ways to Use Water More Efficiently

Effective water-saving measures for urban areas

Modify rate structure to influence consumer water use, including:
- **shifting from decreasing** block rates to uniform block rates
- shifting from uniform rates to increasing block **rates**
- **increasing rates during summer months**
- **imposing excess-use charges during times of water shortage.**

Modify plumbing system, including:
- **distributing water-saving kits, including replacement showerheads and flow restrictors**
- **changing plumbing standards**
- **requiring or offering rebates for ultra-low-flow toilets.**

Reduce water-system losses, including:
- **using watermain-leak-detection** survey teams followed by water main repair or replacement as necessary to reduce system losses
- monitoring unaccounted-for water
- conducting indoor-outdoor audits
- starting a meter-replacement program
- recycling filter plant backwash water
- recharging groundwater supplies.

Meter all water sales and replace aging or defective meters in a timely way.

Reduce water use for landscaping, including:
- imposing lawn watering and other landscape-irrigation restrictions
- developing a demonstration garden
- publishing a xeriscape **manual**
- using nonpotable water for irrigation
- imposing mandatory water-use restrictions during times of water shortage.

Conduct water-conservation education of the public and of school children, including special emphasis during times of water shortage,

Effective water-saving measures for farms

Use lasers for land leveling.
install return-flow systems.
Line canals or install piping to control seepage.
Control phraetophytes (although these plants may be considered valuable habitat).
Use sprinkler and drip irrigation systems.
Schedule irrigation by demand.
Use soil-moisture monitoring.
Use deep pre-irrigation during periods when surplus water is available.
improve tillage practices.
Use evaporation suppressants.
Use lower-quality water.
install underground pipelines.
Grow drought or salinity-tolerant crops.

SOURCE: W. Anton, "implementing ASCE Water Conservation Polk-y," in: Water Resources Planning and Management: Proceedings of *the Miter Resources Sessions at Water Forum '92,* **Water Forum '92, Baltimore, MD, Aug. 2-6, 1992.**

15 M. Moynahan, Metropolitan Water District of Southern California, personal communication, August 1992.

16 Ibid.

conservation are far from being reached, but in the absence of new developments in conservation technology, conservation can be expected to have diminishing returns. ultimately, additional solutions may be needed. Moreover, once the easy options have been implemented, additional conservation may require higher costs and important lifestyle changes, and these may be resisted by the public.

Policy *Options: Improving Demand Management*

Demand management, where practiced, has generally been a State or local concern rather than a Federal one. However, if it chooses to do so, Congress and/or the Executive Branch could stimulate demand management in various ways.

Option 5-1: *Amend the Clean Water Act to allow Federal grants to States for wastewater treatment projects to be used for conservation investments. These* State revolving funds (SRFS) can now be used for sewage treatment facilities but generally not for conservation. However, to the degree that conservation reduces the volume of water that needs to be treated, the cost of sewage treatment is reduced. Grants for SRFS are set to expire in 1994. Congress could continue this funding when it reauthorizes the Clean Water Act and, in Title VI of the Act, could make conservation explicitly eligible for revolving-fund loans. States might, in turn, offer favorable loan terms to communities that achieve suggested water-efficiency goals.

Option 5-2: Lead *by example by promoting greater water-use efficiency in Federal facilities. The* Federal Government owns or leases about 500,000 buildings of various sizes and some 422,000 housing units for military families. It also subsidizes utility bills for some 9 million households of low-income families (77). Thus, Federal facilities and subsidized housing represent an opportunity for the U.S. Government to play an important role in promoting water-use efficiency. Currently, however, Federal agencies have little incentive to conserve water. Most agencies do not even meter their water use or have the baseline data needed to determin the payback period and cost-effectiveness of efficiency measures.

The Energy Policy Act of 1992 (P.L. 102-486) does encourage water conservation in Federal facilities, but, in contrast to the act's detailed treatment of energy conservation, it treats water as an afterthought. Congress should clarify its intent regarding water conservation, including, for example, how funds authorized for efficiency programs are to be divided between energy and water conservation. Congress might direct agencies to: 1) establish programs to reward innovative and/or cost-effective water-conservation measures, 2) use models that predict water use [e.g., the Army Corps of Engineers Institute for Water Resources Municipal and Industrial Needs (IWR-MAIN) model (73) to identify opportunities for improved water-use efficiency, and 3) amend Federal acquisition regulations to facilitate Federal procurement of efficient water-Use technology.

Option 5-3: *Increase funding for the development and use of water-saving technologies. The* Water Resources Research Act of 1984 (P.L. 98-242) authorizes funding for such purposes. However, no funds were appropriated for the act's competitive matching-grant fund in 1993. Moreover, no funds have ever been appropriated under sections 106 and 108 of the act, which specifically authorize grants for water-related technology development, including conservation and water-reuse technologies.

Option 5-4: *Reform tax provisions to promote conservation investments. The* Tax Reform Act of 1986 (P.L. 99-514) clamped down on the ability of cities and States to use tax-exempt bonds to finance any projects except those that clearly benefit the public (72). The benefits of most conservation technology (e.g., plumbing retrofits and advanced irrigation systems) have been considered to be mostly private and, hence, the technology has not been eligible for tax-exempt financing. To promote more conservation investment, Congress may wish to revise the tax code to define conservation investments as having substantial public benefits and, hence, to be eligible for tax-exempt-bond financing.

Option 5-5: *Reform pricing in Federal water projects.* Although it may be difficult to reform the pricing of water supplied by existing Federal projects, Congress could eliminate subsidies on future projects, such as for interest-free repayment of construction costs or loans. Alternatively, Congress could require, through legislation, that all entities that stand to benefit from new, subsidized, federally developed water study and, if necessary, reform their current pricing structures before water is delivered (92). Ignoring possible price reforms would result in inefficient expenditure of Federal funds.

Policy Options: Facilitating Water Marketing

As with demand management, Federal law usually defers to State law regarding water marketing and other transfers. However, the Federal Government could help facilitate mutually beneficial transfers in several ways. It could provide stronger leadership, improve the implementation of its own policies, influence State Governments through the use of incentives or disincentives, and clarify some ambiguous elements of reclamation law. Present uncertainty over the rules governing a market can slow and raise the effective costs of transactions. The Federal Government could also have some influence in helping to ensure that transfers are fair for those not directly involved in the exchange and that they do not adversely affect instream uses of water.

Option 5-6: *Urge the Department of the Interior (DOI) to provide stronger leadership in facilitating water transfers.* In December 1988, DOI adopted a set of principles for facilitating voluntary water transfers involving Bureau of Reclamation facilities. However, the Bureau has not effectively implemented these directives, and they have not been applied consistently in all regions (42). Stronger leadership could include an unambiguous public statement by DOI and Bureau officials endorsing water transfers as a means of solving water resource problems, more emphasis within the Bureau on transfers, and consideration of the recommendations made by the Western Governor's Association (WGA). WGA recommended that DOI work with it to develop a package of amendments to reclamation law to facilitate transfers (%).

Option 5-7: *Clarify reclamation law on trades and transfers.* Reclamation law was written when western settlement and water development were being emphasized and when little or no consideration was given to the transfer of water rights or to contractual entitlements on federally constructed water projects. There are several ambiguities in this body of law regarding the transferability of water. For example, can conserved water be transferred, or does a farmer who saves water by using it more efficiently lose rights to it?[17] It is also at times unclear whether State or Federal law governs transfers on Federal projects. Clarification might be accomplished through a formal solicitor's opinion by DOI or, alternatively, through new legislation.

Option 5-8: *Clarify rules regarding the marketing of Indian water.* The nature of water rights for many Indian tribes is still open to question. A key issue is whether Indian water rights, once quantified, will be salable or leasable, and, if so, with what restrictions. Allowing water entitlements of Indian reservations to be leased with no more restriction than non-Indian rights would facilitate greater efficiency and flexibility of water use. Equity issues regarding Indian water are important and usually controversial. Indians have often been treated unfairly. At the same time, many non-Indians have come to depend on inexpensive water that may legally belong to Indian tribes, and current users could, in theory,

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17 At issue is whether the 1902 Reclamation Act (32 Stat. 388) imposes any additional requirements, beyond those Of State law, for water on Federal projects.

be required by Indians to pay significantly more than they do now. Indian claims have often been settled through legislation, and in some cases, the legislation has specified the degree to which Indian water is leasable (21). Language ensuring the ability of Indians to market water or transfer entitlements could be included in all future Indian water settlements.

Option 5-9: *Provide ways for Federal agencies to buy water for environmental purposes.* Federal participation in water markets could play a role in preserving or enhancing instream uses, a goal that could become increasingly difficult to achieve if water demand increases and/or supply decreases. Water rights for instream-flow purposes are usually held by States but are often junior in nature and could thus be the first to be curtailed during a drought. Stronger protection could be acquired by allowing public agencies charged with protection of fish and wildlife and other instream uses of water to participate in water markets. In States that allow non-State agencies to acquire instream rights, Federal agencies such as the Fish and Wildlife Service could be funded to acquire water rights where existing statutes afford inadequate protection. Flexibility would be enhanced by allowing agencies to make not only permanent purchases of water rights but also short-term purchases during drought periods, when instream uses of water are most likely to be under stress (92).

Supply Management

Opportunities exist for signicant gains in water-use efficiency through better management of existing (i.e., developed) water supplies. Such opportunities may be realized by: 1) improving coordination of water resource management, 2) enhancing the flexibility of reservoir and reservoir-system operations, 3) expanding the conjunctive use of ground and surface water, and 4) taking advantage of new analytical tools and forecast systems.

Improving Coordination

In large part, water resource systems throughout the United States have developed independently of one another, their geographical limits usually coincident with political rather than watershed boundaries. Not surprisingly, water resource management in the United States has evolved in a fragmented and uncoordinated fashion. Coordination has not mattered greatly where water is abundant, but it is becoming increasingly important in those parts of the United States where water resources are becoming relatively more scarce and/or polluted. It will become even more important if global climate change results in decreased water supplies in some areas.

The most efficient way to manage water resources is the comprehensive river basin or watershed approach. At its best, such an approach would entail managing reservoirs in the watershed to meet multiple demands as a single system rather than individually, managing groundwater and surface water jointly, managing water-quantity and water-quality issues together, and integrating floodplain and wetland management with other aspects of water resource management. Managing in this way would not only increase usable water supplies but would also benefit other valuable uses for water (e.g., for habitat and wetlands preservation and for recreation). River basin management would also improve the flexibility and efficiency desirable in policies suited to a changing climate. Comprehensive planning and management is likely to become increasingly important wherever opportunities for developing new supplies grow scarce and water becomes subject to greater competition among competing uses.

The concept of river basin management is not new and, in fact, is widely accepted in theory among water resource professionals, ecologists, and others. However, such management practices are the exception rather than the rule. Although many are aware of the benefits of more-integrated management, coordination and cooperation to this end have been very difficult. Responsibilities for water supply are generally separate from those for water quality; responsibilities for groundwater are often separate from those for surface water; Federal goals and responsibilities within a basin may conflict with State or local ones; and Federal and State boundaries seldom coincide with groundwater basins or surface watersheds. The diversity and inflexibility of water-rights laws, inadequate incentives for efficiency in water use, and inadequate research, information, and training support for improved water resource coordination practices can also make river basin planning difficult (72).

Nevertheless, river basin and watershed planning is attracting renewed attention. The U.S. Environmental Protection Agency strongly supports the approach, and its regional offices are now participating in about 35 small watershed projects around the country (82). Moreover, legislation recently introduced to reauthorize the Clean Water Act (S. 1114, the Water Pollution Prevention and Control Act of 1993) contains important watershed-management provisions, including some for designating areas for watershed management, developing watershed-management plans, and providing for incentives and public participation.

Reservoir and Reservoir-Systern *Management*

Individual reservoirs are often designed and constructed by one jurisdiction (e.g., a water district). The operating rules for the reservoir are also usually centered around meeting the needs of the clients of the constructing agency, given the storage and delivery constraints imposed on the reservoir when it was constructed. Where there are several reservoirs on a river system (possibly operated by different jurisdictions or even in different States), yield of the system as a whole can often be increased if joint operational rules are considered. For example, rather than meeting the downstream demands of a particular area solely from the reservoir owned by that jurisdiction, more than one upstream reservoir may often be used. If the timing and amount of releases can be coordinated, often everyone can gain.

Discovering and taking advantage of these opportunities involve a good deal of coordination among different water agencies and include such tasks as developing flow and storage models that are accepted by all of the jurisdictions involved; simulating likely stress events, such as floods and drought; studying trial responses to such simulated events; and developing written agreements for joint operation of facilities. It often takes years and the commitment of key individuals to implement these steps, but the effort can be very successful.

For example, starting in 1977, the Interstate Commission on the Potomac River Basin (ICPRB) sponsored several studies of the potential for joint, rather than independent, operations during drought periods among the three principal Washington, DC, water suppliers. Using a river-simulation model developed at Johns Hopkins University, ICPRB determined that existing reservoir capacity was underutilized, and that if the local water suppliers would coordinate the timing of withdrawals from upstream reservoirs, they would be able to increase system yields dramatically and avoid spending large sums on construction of new reservoirs. A series of written agreements was approved in 1982 specifying how joint operations would be carried out during droughts. Joint management of existing facilities in the Potomac River Basin increased system yields by over 30 percent (about 90 million gallons per day). Between $200 million and $1 billion was saved, compared with previously evaluated structural alternatives for meeting future supply needs, and environmental impacts were substantially reduced (63).

The potential exists throughout the Nation for improving operational efficiencies of multi-reservoir systems through systems analysis. Moreover, the Federal role in contingency planning and systems-analysis studies could be large because federally constructed reservoirs are often intermingled with nonfederal reservoirs on the same river system. The Colorado River System is one important prospect for application of more-efficient operating rules. The Bureau of Reclamation operates all major storage facilities on this river, whose water is so crucial to the arid Southwest. Potentially, results of Federal simulations of long-term water availability on the Colorado (including analysis of various climate change scenarios) could ease the way for Colorado River Basin States to begin considering new operating rules of mutual benefit.

An important reason for the difficulty in making efficiency and flexibility improvements in the management of reservoir systems (and individual reservoirs) pertains to the process by which Federal water projects are authorized and regulated. The two agencies responsible for most large Federal water projects are the Army Corps of Engineers and the Bureau of Reclamation. Both the studies and the projects these agencies undertake are authorized by Congress. The projects are usually based on a detailed feasibility study by one of the two agencies. Both the study and the subsequent congressional authorization typically emphasize individual projects, and the operating agencies are closely bound to use projects only for the original purposes specified in authorizing legislation. Rarely do the computed benefits from a project reflect what might be achieved if the operation of the project were integrated in a systematic way with other existing and proposed projects, either Federal or local.

Initially, most new projects are more than adequate to serve the existing demands. Over time, however, demands may increase, and structural or operational changes may be required. Historically, structural changes (i.e., construction of new storage facilities) have been emphasized, and opportunities for "creating' more water through better management and/or reallocation have received little attention. This may occur because there is no regular review process devoted to finding such opportunities and because whenever changes in operating policies are proposed, there are inevitably people who believe their interest lies in maintaining the status quo (64).

Conjunctive Use of *Groundwater* and Surface Water

Groundwater and surface supplies are managed independently inmost States and are governed by different legal systems and separate agencies. The integrated management of ground and surface water, often referred to as *conjunctive management,* has the potential to significantly improve water-system performance and increase the flexibility and reliability of water resource management (see box 5-I).

Storage of water underground is desirable because it makes possible the use of water that otherwise would not be captured (20). Conjunctive management can be used to balance seasonal variations in water supply and demand, enabling groundwater to be used in lieu of surface water during dry periods; to eliminate the need for additional treatment and surface-distribution facilities; to allow water suppliers to meet customer demands more cheaply and easily than would be possible through independent management of separate systems; and to enhance yields through less-conservative operation of existing storage facilities (e.g., a conjunctive management study of Houston found that system yields could be increased by 20 percent (63)). Another conjunctive use is blending surface and groundwater to produce an overall usable medium-quality supply (e.g., by blending high-quality surface water with brackish groundwater not otherwise usable).

Cities such as Los Angeles, Phoenix, Albuquerque, and Houston already have conjunctive-use plans, but conjunctive management is still not used in most major population centers (72). Not all communities have access to groundwater supplies, but conjunctive management may be feasible for some that do not, as long as they are linked to a river or distribution system. Each plan is unique, and the most equitable and efficient approaches are closely tailored to the physical characteristics of the water resources (e.g., rates

Box 5-I-Seasonal Storage: The Metropolitan Water District's Interruptible Water Service and Seasonal Storage Programs

Rainfall and snowmelt tend to be seasonal events, so the availability of water supplies in communities that rely on surface water can vary widely during the course of the year. Water demand also varies with the seasons, typically being much higher during the summer and lower during the winter. Balancing supply and demand in the face of these variations is possible only with the use of storage facilities. Southern California's Metropolitan Water District (MWD) has used its Interruptible Water Service (IWS) Program and its Seasonal Storage Program (SSP) to encourage conjunctive management as a method of enlarging local storage capacity.

The IWS Program began in 1981 when MWD offered to sell water at discounted rates to member agencies that could demonstrate an ability to continue serving customer needs in the event that water deliveries from MWD were interrupted (44). Operation of the program allowed MWD to take advantage of excess supplies in the Colorado River and the State Water Project by delivering the water to local agencies when it was available and ceasing the deliveries when it was not. Most of the local agencies chose to meet the IWS requirements by developing new artificial-recharge and pumping facilities to store the water underground and then pump it back out during supply interruptions.[1]

The IWS Program led to problems for some participating agencies, however. Retail agencies were required only to demonstrate sufficient local production capacity to continue making customer deliveries in the event of MWD interruptions, rather than agreeing to actually store the water in new or underutilized facilities. Some agencies found that they were able to demonstrate this capacity on paper much more easily than they were actually able to produce the water when needed.[2]

MWD discontinued the IWS Program and replaced it with the SSP in 1989. The concept is the same: discounted water is used to encourage MWD's retail-agency members to develop local facilities for storing excess winter flows for subsequent use during low-flow, high-demand summer months. But terms of the SSP require local agencies to actually store the water, either directly in surface reservoirs and aquifers or indirectly by using the water in lieu of existing groundwater pumping (44). MWD has found that the SSP has encouraged development of local storage capacity, eased peak demands on the MWD delivery system, and worked better for the retail agencies than the program it replaced. An additional benefit is that MWD's energy costs for pumping the water to its service area are lower in the winter than in the summer.[3]

1 D. Adams, Director of Resources, Metropolitan Water District of Southern California, Los Angeles, personal communication, July 1992.

2 Ibid.

3 Ibid.

of discharge, the degree to which groundwater is connected to surface supplies, the rate and amount of lateral movement within the groundwater basin, and the susceptibility of the basin to degradation from saltwater intrusion or other sources).

As with integration of surface-reservoir systems, conjunctive management can provide the robustness and flexibility desirable for adaptation to climate change. Similarly, however, a profusion of ground and surface-water laws, regulations, and agencies may be involved in a single conjunctive management project, so agreements can take a great deal of time to negotiate. This amount of time may diminish as experience with different schemes grows.

Analytical Tools and Forecast Systems

The state of the art of analytical tools used by water resource managers has improved significantly in recent years. Various types of models currently being developed or refined could dramatically improve water resource decisionmaking, for example, by providing information about how benefits from competing demands for water could be optimized, how pursuit of a particular water-management goal could affect competing goals, how major land-use changes in a basin (e.g., urbanization) could affect water availability, or how environmental quality could be improved. Many of these tools, however, are not yet available or are not being used routinely.

Several agencies have small programs or initiatives to develop and implement tools for advanced hydrologic and climate forecasting to reduce risk in water-management decisions. For example, both the U.S. Geological Survey and the Bureau of Land Management have been working with the University of Colorado's Center for Advanced Decision Support for Water and Environmental Systems (CADSWES). CADSWES is helping the agencies develop anew generation of water resource modeling systems. A joint pilot project using these new systems has recently been planned to study the sensitivity of several western areas-the Gunnison River Basin and the American, Carson, and Truckee Basins-to climate change (51).

The National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service also has an advanced modeling initiative, the Water Resources Forecasting System (WARFS). The goal of this program is to provide improved stream-flow forecasting, building on existing river and flood-forecasting services and NOAA's weather- and climate-forecasting capabilities, its planned Next Generation Weather Radar program, and its Automated Surface Observing System. The Denver Water Department and the Bureau of Reclamation, among other groups, have recently used the methodology in a pilot program to increase water yields from three reservoirs serving the Denver area while optimizing benefits from other competing demands such as hydropower and recreation (39). The Extended Streamflow Prediction component of WARFS will allow a hydrologist to make extended probabilistic forecasts of values of stream flow and other hydrological variables, which can be used for flood-control planning, drought analysis and contingency planning, and hydropower planning.

The Army Corps of Engineers has developed several models that, among other things, enable communities to evaluate demand-management programs and allow systems operators to consider alternative operating strategies (e.g., the Corp's IWR-MAIN model). Much of the new software available is significantly more uier-friendly than earlier versions, enabling models to be built quickly, more easily, and at a fraction of the cost. The Corps' research laboratories have also been developing innovative methods and models for analyzing water-environment problems that are not traditionally part of its mission.

The new analytical tools, promising as they are for improving water resource management, are based on the assumption that the climate of the future will be similar to the climate of the past. Thus, historic patterns of temperature and rainfall have been assumed to provide a good indication of the range of expected future values. Climate change may mean that the assumption of a stationary climate may no longer be the best predictor of future conditions. Hence, some procedures currently used to plan and design dams and other structures and to conduct hydrologic analyses may need to be modified to account for this additional source of uncertainty. Among these procedures may be those used in flood-frequency analysis for floodplain planning, in determining the probable maximum flood or design flood for darn design and darn-safety analysis, in statistical analyses of historic runoff patterns for reservoir-system planning, and in stream-flow forecasting for reservoir operations and flood control.[18]

[18] B. Miller, Tennessee Valley Authority, personal communication, 1993.

Policy Options: Improving Supply Management

Systems integration and the reallocation of supplies based on current needs could provide significant gains in water-management efficiency and flexibility, and there appear to be many opportunities for such gains. Several ways that the Federal Government could promote better management are considered below.

Option 5-10: *Resurrect the former Water Resources Council or create a similar high-level coordinating body.* A new council or committee could play an important role in improving cooperation and coordination among the many Federal agencies with water-related responsibilities and among Federal, State, and local governments and the private sector. The new council might be strengthened relative to the original one by appointing a full-time chair, who would report directly to the President. It could be charged with reviewing interagency and intergovernmental policies and programs to promote consistency, fairness, and efficiency and, more generally, with elaborating and overseeing national water policy. The original council was established by the Water Resources Planning Act of 1965 (P.L. 89-80). Legislatively, this council still exists, but Congress would need to restore funding for it.

Option 5-11: *Promote the reestablishment and strengthening of Federal-State river basin commissions as another way to improve coordination among agencies.* River basins, not political jurisdictions, are the natural management units for water. Integrated management can only work if the multiple parties with jurisdiction in any given watershed can be brought together in some way to explore common problems and pursue joint solutions. Section 321 of the Water Pollution Prevention Control Act of 1993 addresses watershed management and could be broadened, if desired, to explicitly address the formation of new Federal-State commissions. The Interstate Commission on the Potomac River Basin (ICPRB) or the Delaware River Basin Commission (DRBC) could serve as models.

ICPRB is jointly funded by member States and the Federal Government. It serves as a neutral ground for the basin States and the Federal Government to discuss mutual problems. Although ICPRB has no regulatory authority, it does provide sophisticated technical assistance in solving problems around the basin. The combination of political neutrality and technical competence has allowed ICPRB to successfully mediate many disputes. To promote establishment of this type of river basin commission, Congress could establish a grant program to make funds available (e.g., for establishing technically competent staffs) to groups of States that choose to negotiate such compacts.

DRBC, in contrast, was established with considerable authority to control the diversion of surface and groundwater within the Delaware River Basin; coordinate Federal, State, and private reservoir releases during droughts; and limit pollution discharges. Individual States have retained veto power over all decisions, but DRBC has proved relatively effective as a setting for negotiating disputes. A Federal representative is a co-equal member of the commission. The DBRC policy was fully implemented only after many years and much controversy, but in its present shape, it could serve as a model for other States.

Option 5-12: *Require the Army Corps of Engineers and the Bureau of Reclamation to undertake periodic audits to improve operational efficiency.* Currently, the agencies do not systematically reassess project operations to meet changing social and economic trends (although extreme events may trigger a reallocation study), nor is legislation authorizing a project systematically reviewed to determine whether it needs to be updated. Congress would need to give the operating agencies a clear mandate to do such studies, and appropriate additional money for this task.

Option 5-13: *Enhance the ability of the Army Corps of Engineers and the Bureau of Reclamation to modify operations of projects to meet changing conditions.* Currently, operating rules based on project authorizations going back many decades appear to give the operating agencies little latitude to improve operations or to respond in the most effective manner to droughts, and what little flexibility exists is difficult to exercise when water is in short supply (64). Many changes either require or are perceived to require legislation before they can be legally implemented. The authorization for a project need not require that the expected benefits of the project be derived from that project alone.

To fully achieve the potential benefits of operating several reservoirs as a system, either for dealing with the possible impacts of climate change or for simply improving the current management of water resources, Congress could give the Army Corps of Engineers and the Bureau of Reclamation the administrative flexibility to deliver the expected benefits in the most effective manner (or, in cases where such flexibility is available, clarify its extent). New legislation, perhaps as part of the next omnibus water bill, likely in 1994, would probably be required. Where additional benefits can be created through systems management (e.g., additional water and increased power revenues). Congress would need either to direct the agencies in how to distribute these benefits or direct them to develop a procedure for doing so.

Option 5-14: ***Tie** funding of Federal water projects to adoption of improved water-management practices by the States-such as* developing State groundwater management plans, facilitating transfers, and improving demand management. There is some precedent for using incentives or disincentives to encourage desirable activity. For example, in exchange for supporting funding of the Central Arizona Project, the Secretary of the Interior required that the State of Arizona adopt a groundwater law aimed at reducing pumping to a safe annual yield (92). Similarly, it may be possible for the Federal Government to require a State to adopt laws that facilitate water transfers before the State can receive Federal funding for projects or other activities.

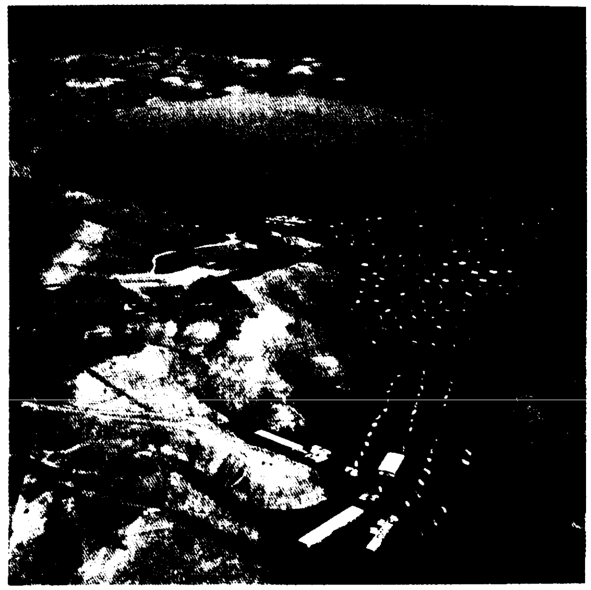
Option 5-15: *Increase finding for the development and promotion of new analytic tools in systems-analysis studies. These* new tools promise a substantial payoff in improved water resource management, but funding for agencies to develop them has been inadequate. NOAA, for example, has so far been unsuccessful in getting sufficient funds for its WARFS initiative. Water resource research funding for the U.S. Geological Survey (USGS) has been cut substantially in recent years. Congress might also want to consider facilitating the development of analytical tools that incorporate climate uncertainty into traditional hydrologic analyses.

Available modeling and forecasting tools (e.g., the IWR-MAIN model) have not been widely disseminated and used by State and local agencies. If Congress wishes to promote the greater dissemination of these tools, it could increase funding under Section 22 of the Water Resources Development Act of 1974 (WRDA, P.L. 93-251). These funds are available for training and technical assistance to States and water utilities for a variety of traditional water resource management needs. Section 22 could also be extended to cover problems that cross over from water resource management to environmental systems management (e.g., watershed management and wetland restoration).

Extreme-Events Management: Droughts and Floods

Natural climate variability almost guarantees that the signal of climate change will be difficult to detect. Drought and floods are among the most extreme expressions of this variability, and whether or not climate change is definitively detected, they will continue to occur. However, more-intense, longer-lasting, or more-frequent extreme events such as these could occur in some areas in a warmer climate (43).[19] If this happens, societal vulnerability would increase and would pose new challenges for public institutions and the private sector.

Both floods and droughts cause significant losses to human and natural systems. For example, costs and losses from the 1988 drought, during which roughly 40 percent of the United States was severely affected, have been estimated to be at least $39 billion (57). For this reason, potential changes in the extremes of these events are perhaps of even more concern than are long-term changes in temperature and precipitation averages. Effective management of floods and drought is extremely important if their impacts are to be minimized. Just as in the supply-management issues discussed above, lack of coordination among and within levels of government has been and continues to be a key constraint to more-effective management. Some near-term improvements in how extreme events are managed would help mitigate any surprises that climate change could bring.



STATE OF CALIFORNIA, DEPARTMENT OF WATER RESOURCES

Six years of drought in the western United States reduced water supplies stored in reservoirs and ma& water resource management much more difficult. Low water levels are conspicuous in the amount of bare earth exposed in this aerial view of Luke Oroville. The California State Water Project begins here, where water from the Feather River watershed is stored.

Droughts

Drought, although difficult to define precisely, is generally the consequence of a natural reduction in the amount of precipitation received over an extended period of time (usually at least a season). A drought's severity can be classified by its duration, intensity, and geographical extent. Factors such as high temperatures, high winds, and low relative humidity are often associated with the occurrence of a drought and can significantly aggravate its severity. The demands made by human activities and vegetation on a region's water supplies are sinificant factors affecting how large the societal and ecological impacts of a drought will be. Population growth and increasing competition for water will lead to greater vulnerability to drought; the potential for climate change provides an additional incentive to improve drought management.

Drought impacts are usually less obvious than flood impacts (e.g., drought rarely results in structural damage). Impacts typically accumulate slowly over a considerable period of time, and they may linger for years after the drought itself has ended. For these reasons, the effects of drought on society, the economy, and the environment are more difficult to quantify, and the provision of disaster relief is thus more challenging. Droughts can provide instructive, if imperfect, analogs to climate change, illustrating problems that could occur more often in a warmer climate (24, 57).

Government responses to previous droughts (e.g., in allocating water from Federal multipurpose reservoirs, providing disaster assistance,

19 Extreme events could also become less intense, shorter, or less frequent in different areas-the picture is not yet clear-but the results would be of less concern and are not pursued further here.

fighting fires, and protecting wildlife refuges) suggest that drought policies could be much more effective than they are now (100). U.S. drought policy is essentially based on the sentiment that drought is a rare and random event rather than on the reality that it is a normal part of climate variability. As such, Government response to drought has typically been reactive rather than proactive, usually focused on crisis management rather than risk management. Significantly, only 23 States had drought plans in 1992, and most of these were inadequate (99, 100). The weakness of the reactive approach is evident in the uncoordinated, untimely, and largely ineffective response efforts that have characterized past droughts (101). Drought relief, at least as it is usually provided now, has often been a disincentive to adopting strategies to minimize risks associated with drought, such as purchasing crop insurance, and may unintentionally reinforce some poor management practices (see ch. 6).

Many studies, including, those of the Western Governors Policy Office (1978), the General Accounting Office (1979), the National Academy of Sciences (1986), the American Meteorological Organization (1990), and the Interstate Council on Water Policy (1987, 1991), summarized in a recent report (100), have called for improvement of drought contingency planning. Most have urged development of a national drought plan that would better define the respective roles of the various agencies that have drought-management responsibilities; promote coordination among Federal agencies and among Federal, State, and local levels of government; establish eligibility, repayment, and other requirements for drought assistance; and provide such assistance in a more timely, consistent, and equitable manner. Although such objectives appear to have considerable merit, not much progress toward meeting them has been made to date. A new study by the U.S. Army Corps of Engineers-a recently completed 4-year assessment of drought management—could provide the basis for developing a national policy for improving water management during drought (95).

The United States may benefit from studying the new Australian drought policy. It applies only to agricultural drought and is based on the philosophy that drought should not be considered a natural disaster but, rather, as part of a highly variable climate and one of the risks farmers face in managing farm operations. Rather than emphasize drought relief, the Australian Government stresses provision of high-quality information so farmers can make better decisions, offers incentives to farmers to adopt sound drought-management practices, and discourages farmers who pursue unsustainable farming practices in drought-prone areas from relying on drought relief (98). The long-term goal of this policy, which could also be used to promote sound practices in other sectors affected by drought (e.g., urban areas), is to reduce vulnerability to drought, increase productivity, improve the allocation of resources, and enhance self-reliance.

Executive Order 12656, signed by President Reagan in November 1988, is intended to guide emergency water planning and management responsibilities of Federal agencies. The order specifies a lead role for the Corps of Engineers for national security emergency preparedness for the Nation's water resources, including coordination of planning activities at the national, regional, State, and local levels (75). This order could provide a vehicle for bringing together relevant agencies to focus on both drought and flood management. However, it has thus far had little impact. The Corps' own 1992 study of the status of emergency preparedness concluded that, despite the order, coordination of activities had not improved. Among other things, the study noted the absence of an overall Federal framework clearly defining the agency responsibilities described by the order, an absence of a clear definition of the types of disasters for which plans are to be developed, the low level of staffing and funding assigned to emergency planning, and, perhaps most significantly, resistance on the part of other Federal agencies and State officials to giving the Corps control over emergency planning (75).

Floods

Floods affect smaller areas than do droughts and are shorter-lived events but are, along with droughts, among the most costly of weather-related phenomena.[20] The importance and challenge of managing floodplains and mitigating flood losses are underscored by the costs of floods in dollars and lives: between 1979 and 1988, average damages from flooding amounted to about $2.4 billion per year, and an average of 95 deaths each year is related to flooding (102). Parts of each of the 50 States have experienced flooding (28) and, in all, about 7 percent of the U.S. land area is subject to occasional flooding. Principal areas subject to flooding are along rivers and adjacent to lake shores and sea coasts. Flash flooding along arroyos and ephemeral streams is of special concern in the arid Southwest (102).

Since the 1930s, considerable progress in mitigating flood damages has been made. Both structural (e.g., building reservoirs and levees) and nonstructural approaches (including flood forecasting and implementing floodplain regulations) have been used. The success of the National Flood Insurance Program (NFIP), created in 1%8, is supported by the fact that more than 18,000 of the 22,000 flood-prone communities in the Nation now participate in the program, and most of the 40,000 stream miles in the United States have been mapped for flood risk (103). Also, important technical improvements in flood forecasting and warning systems have been made.

Despite the progress, however, flood darnage is increasing at about 1.5 percent every year (about $200 per 1,000 people per year) (19). An update of a 1987 study for the Federal Emergency Management Agency estimated that 9.6 million households and $390 billion in property are at risk from flooding (5). Mitigation has fallen well short of what was expected when current policies and activities were initiated. Also, some trends and disturbing problems indicate that despite recent efforts, vulnerability to flood damages is likely to continue to grow: 1) populations in and adjacent to flood-prone areas, especially in coastal areas, continue to increase, putting more property and greater numbers of people at risk, 2) flood-moderating wetlands continued to be destroyed (see vol. 2, ch. 4), 3) little has been done to control or contain increased runoff from upstream development (e.g., runoff caused by paving over land), 4) many undeveloped areas have not yet been mapped (mapping has been concentrated in already-developed areas), and people are moving into such areas without adequate information concerning the risk, 5) many dams and levees are beginning to deteriorate with age, leaving property owners with a false sense of security about

STATE OF CALIFORNIA, DEPARTMENT OF WATER RESOURCES

Every State has experienced some flooding at one time or another, and as more people move into flood-prone areas, the exposure of people and property to potential flood risks increases. The homes shown here were flooded in 1986 when the Yuba and Bear Rivers overflowed their banks near Marysville, California.

[20] See chapter 4 for a more detailed discussion of floods in coastal areas.

how well they are protected, and 6) some policies (e.g., provision of subsidies for building roads and bridges) tend to encourage development in floodplains (38).

Climate change could increase flood risk. Although considerable uncertainty exists, climate change could bring more-frequent and/or more-intense floods. Given that development in and near floodplains is expected to last a considerable period of time and that 'the Nation's ability to predict the magnitude and frequency of future events is still limited, it may be prudent to consider the potential effects of climate change when decisions are made (or revised) about the type and amount of development allowed in vulnerable areas. In the absence of sufficient data, flexible and cautious policies are preferred.

An important constraint to better floodplain management mirrors a common constraint in other areas of water resource management: many Federal agencies have some flood-control responsibilities, and they are often unable to work in a coordinated fashion. The four principal Federal agencies involved in construction, operation, and maintenance of flood-control facilities are the Army Corps of Engineers, the Bureau of Reclamation, the Soil Conservation Service, and the Tennessee Valley Authority. The multiple missions of these agencies overlap, and agencies may disagree on who is in control and what structures should be built and for what purposes. The Federal Emergency Management Agency (FEMA) plays an important role in administering the NFIP and disaster assistance. The involvement of State and local agencies, the private insurance industry, and developers, all with different goals, adds to the difficulty of coordination (19).

In practice, no truly unified national program for floodplain management exists, nor are there many examples of effective regional bodies. Such a unified plan could be of" great value in sorting out the respective roles of" each level of government and the private sector, in establishing the relative importance of multiple floodplain management objectives (including flood-loss reduction and natural-value protection), and in promoting implementation strategies.

An even broader problem is that floodplain management is usually addressed separately from other aspects of water resource planning and land-use policy. Ideally, regional floodplain management would be considered as part of a broader plan addressing in addition water-quality and -quantity issues, habitat and open-space preservation, and other land-use and development concerns (19) (see vol. 2, chs. 4, 5, and 6).

Policy options for Improvlng Drought Management

Previous drought-assessment and -response efforts have suffered from the lack of coordination of activities at the Federal level and from lack of coordination among Federal, State, and regional drought-management activities. Greater integration of activities could be fostered in several ways and could help reduce vulnerability to future droughts and enable scarce resources to be used more effectively.

Option 5-16: *Create an interagency drought taskforce with the authority to develop a national drought policy and plan.* Congress could do this or the authority of existing Executive Order 12656, which was established to guide emergency water planning and management responsibilities of Federal agencies, could be used. Such a plan should define specific, action-oriented response objectives and contain an integrated strategy for implementing them. Leadership of the task force could be either a designated lead agency or the Office of the President. All Federal agencies with drought-related missions and representatives of State Government, regional organizations, and the private sector should be included. Results of the Corp's National Drought Management Study, the most recent Federal effort, would provide a good point of departure (95).

As part of the development of national policy, Federal agencies' drought-relief programs should be reviewed, including, for example, soil- and water-conservation programs and the Federal Crop Insurance Program. These reviews should

Table 5-3—Possible Risk-Management and Risk-Minimization Measures the Federal Government Could Consider to Lessen the Effects of Drought

Assessment programs
- Develop a comprehensive, integrated national drought-watch system (NDWS)
- Inventory data availability in support of an NDWS
- Develop new indexes to assist in the early estimation of drought impacts in various sectors
- Establish objective "triggers" for the phase-in and phase-out of relief and assistance programs

Legislation, public policy
- Develop a national drought policy and plan
- Examine Federal land-use policies to ensure appropriate management of natural resources and consistency with national drought policy
- Review all Federal drought-relief-assistance programs, Federal crop-insurance program, and other agricultural and water policies for consistency with national drought policy

Public-awareness programs
- Establish a national drought-mitigation center to provide Information to the public and private sectors
- Improve data information products and delivery systems to provide timely and reliable information to users
- Develop and implement water-conservation-awareness programs

Drought-preparedness planning
- Promote the establishment of comprehensive State drought plans
- Promote intergovernmental cooperation and coordination on drought planning
- Evaluate worst-case scenarios for drought management
- Evaluate the potential effects of climate change on regional hydrology and its implications on Federal and State water policies
- Promote the establishment of drought plans by public water suppliers
- Conduct post-drought audits of Federal drought-assessment and -response efforts

SOURCE: D. Wilhite, "Drought Management and Climate Change," contractor report prepared for the Office of Technology Assessment, December 1992.

include taking an inventory of current assistance programs and their eligibility requirements, identifying overlapping responsibilities, and examining the distribution of financial resources to relief recipients. Reviews could also examine the timing and effectiveness of relief.

Additional components of a national drought policy could also include:

1. *Adopting risk-management and risk-minimization practices such as those listed in table 5-3.* Federal agencies could consider following the lead of Australia, where the government does not ignore the need for assistance during severe drought but promotes more self-reliance while at the same time protecting the natural and agricultural resource base. Drought relief, for example, could be made contingent on adopting ways to minimize drought risk (e.g., buying crop insurance) (see ch. 6).
2. *Supporting post-drought audits of assessment and response efforts.* All episodes of severe drought in the United States provoke some degree of response from the Federal Government. At times, such as during the 1974-77 and 1988-89 droughts, massive levels of drought relief are targeted for the stricken area. However, comprehensive post-drought audits of assessment and response efforts are not routinely conducted. Audits could identify successes and failures of recent efforts and provide a basis for revising drought policies to improve future responses. An interagency task force might direct university or private research groups to conduct the audits to avoid appearance of bias.

3. *Developing a national drought-watch system. The* climate-related monitoring activities of the Federal Government are split among many agencies and subagencies, which means that a comprehensive national assessment of drought conditions does not exist. Given that recognition of drought can be slow, a national early-warning system would be useful to support a more proactive national drought policy and plan. Several specific actions might be considered: 1) create a national drought-watch team, possibly under the authority of the interagency drought task force, to routinely assess precipitation, temperature, soil moisture, groundwater levels, stream flow, snowpack conditions, runoff potential, and reservoir and lake levels, and 2) create a national agricultural weather-information office within the U.S. Department of Agriculture (USDA) to address more adequately the needs of the agricultural community for climate-related information. Such an office would provide a focus for existing USDA weather-related programs and would oversee needed new ones.

Policy Options for Improving Flood Management

The Federal roles in flood management include overseeing national flood policy, coordinating floodplain management efforts, providing technical guidance and education, and regulating and funding some State, local, and private activities. Some options that may promote these roles and introduce greater efficiency and flexibility into flood management are considered below. Others, including possible reforms of the NFIP, are discussed in the context of coastal development in volume 2, chapter 4.

Option 5-17: *Create a national flood-assessment board, to consist of representatives of Federal, State, and local agencies and the private sector. The* board could establish a set of national goals for floodplain management together with a timetable for their achievement, assess existing Federal flood programs and responsibilities, recommend changes in missions of Federal agencies to eliminate overlap, and assign responsibilities where gaps occur.

Such a board could also promote the refinement and implementation of State floodplain management plans. Much energy has already been expended on developing State and local mitigation plans, but these plans are often more paper exercises than practical guides to action. Plan implementation could be aided by developing a model floodplain management plan, conducting regional training programs, and expanding efforts to educate the public about the nature of flood hazards and the natural values of floodplains.

The board could facilitate multiobjective flood plain management. Floodplains may contain homes, businesses, recreation sites, fish and wildlife habitats, and historic sites, among other things. Each of these features is usually managed separately rather than as an integrated package, and conflict among different interests is often the result. The Federal Government could do more to facilitate State and local programs to manage in a more integrated fashion by, for example, providing technical assistance and grants-in-aid. As part of the Clean Water Act reauthorization, Congress could provide incentive grants to States or communities that undertake multiobjective watershed-management initiatives.

Finally, the board might be directed to conduct an evaluation of various programs and activities (such as FEMA's) to determine their effectiveness or to assess how to improve the acquisition and utilization of data on flood damages. An interagency flood-insurance task force has been proposed in Title V of H.R. 62, the National Flood Insurance Compliance, Mitigation, and Erosion Management Act of 1993, that could, as currently envisioned, undertake this activity. However, State, local, and private participation on the flood-assessment board would, in general, improve its effectiveness.

Option 5-18: *Direct the National Flood Insurance Program to base risk calculations on anticipated development, rather than on current development.* Recognition of the impact of increased runoff on flood damage is a weak area in the National Flood Insurance Program. Currently, floodplain delineation is based on the development that exists in the basin at the time the hydrologic and hydraulic studies are done (19). As development in the basin increases, peak flows and volumes increase, which will result in a change in the 100-year flood, possibly turning it into a 50-year or lo-year event. A changing climate would also alter future flood risks and might similarly be considered to the extent possible. The long-term benefit of this policy would be to prevent or alter construction in areas that could become (or are likely to become) flood-hazard zones in the future.

Supply Augmentation

Several alternatives exist for augmenting supplies of water. These include, among others, expanding the capacity to store water that could not be used immediately and would otherwise not be available for use later, desalting sea (or brackish) water, diverting water through new pipelines and aqueducts from low- to high-demand areas, and treating and reusing wastewater.

Reservoirs and Climate Change

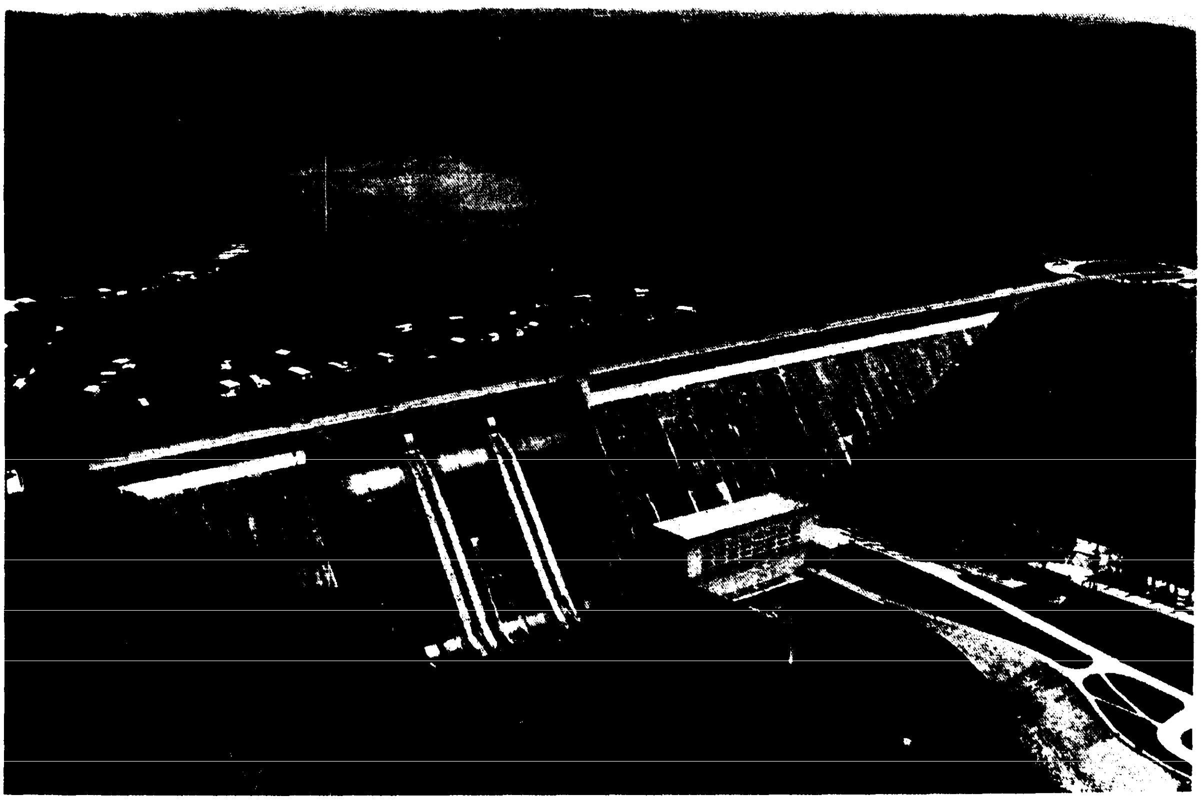
Periods of high water demand rarely correspond to times of high water supply. Building reservoirs has been a common solution to the problem of storing water during high-flow periods and releasing it for later use as needed. Currently, there are more than 2,650 reservoirs in the United States with capacities of 5,000 af or more. The combined capacity of these reservoirs is about 480 million af, of which 90 percent is stored by the 574 largest. There are also at least 50,000 smaller reservoirs, with capacities ranging from 50 to 5,000 af (14).

After decades of reservoir building, the Nation's reservoir infrastructure is largely in place. There are still opportunities to build additional reservoirs, but the pace of new construction has slowed dramatically in the past decade. One reason for the slowdown is the high cost of new reservoirs and the scarcity of available funds. A second is the fact that there are relatively few good undeveloped sites left. In addition, public attitudes about the environment have changed, and many people no longer believe that the benefits of new-reservoir construction outweigh the costs. Reservoirs have destroyed substantial riparian habitat, blocked free-flowing sections of rivers, interrupted migration corridors, and deprived downstream wetlands of sediment. Consequently, it is now very difficult politically to build major new dams.

Currently, climate change is not explicitly considered by the Nation's largest reservoir operator-the Army Corps of Engineers, the Bureau of Reclamation, the Soil Conservation Service, or the Tennessee Valley Authority-in renovating or managing existing reservoirs or in planning and designing new ones. Uncertainty about the regional impacts of climate change on runoff makes it difficult to justify changing design features or operating rules at this time (67). Also, the high fixed-discount rate used in cost-benefit analyses heavily discounts those benefits of a new project that might occur several decades in the future. Hence, when standard economic discounting rules are used, specific features integrated into reservoir design to anticipate climate change would be difficult to justify economically. Finally, the Corps argues that reservoir-design criteria have been based on an engineering-reliability -based strategy that builds in considerable buffering capacity for extreme meteorologic and hydrologic events. Thus, many of the 500 largest existing reservoirs may already have the capacity and operating flexibility desirable to cope with a changing climate (27).

Still, many existing reservoirs are currently in need of major or minor rehabilitation. As rehabil-

TENNESSEE VALLEY AUTHORITY



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itation work is undertaken, engineers could consider whether regional climate change data or costs justify modifications based on anticipated climate change. The need for more storage space or flood-control capacity could sometimes be satisfied by undertaking such structural modifications as increasing the height (which often also requires increasing the bulk) of a dam and enlarging its spillway. (Even without considering climate change, many small, nonfederal dams and a few Federal ones lack adequate spillway capacity.) Enlarging a reservoir is not without environmental costs because additional land would be inundated. Where feasible, temperature-sensitive fish species downstream from a dam could be accommodated by mixing the colder, deeper water in a reservoir with warmer, surface water. Such temperature control can be accomplished by retrofitting multiple-level outflows to a dam's outlet works .21 Enlarging one reservoir in a reservoir system may also allow the entire system to be operated more flexibly (see Supply Management, above).

Despite concerns about reservoirs, some new ones are likely to be required (even if not specifically in response to climate change). Generally, anew reservoir would be a robust response to the uncertainty of climate change-it would

21 This would cost about $85 million for Shasta Darn in Northern California, for example.

U.S. DEPARTMENT OF THE INTERIOR, BUREAU OF RECLAMATION

The Yuma Desalting Plant is the world's largest reverse osmosis unit. Located in southwestern Arizona just north of Mexico, the plant desalts highly saline drainage water from farmlands east of Yuma before the water enters the Colorado River. This operation lowers the overall salinity of the Colorado and enables the United States to meet its treaty obligation to deliver water of acceptable quality to Mexico.

allow greater operational flexibility whether the future brought more intense droughts or more floods. However, a reservoir is also a fixed, permanent structure, so before large amounts are spent on an irreversible decision, the costs and benefits of a new reservoir should be weighed against those of other adaptation options. For those new reservoirs required, overbuilding as a response to uncertainty may no longer be appropriate or feasible. Given high costs, the trend toward reduced Federal contributions to water-project construction, and upfront financing requirements, new reservoirs are likely to be smaller and will probably be designed with less buffering capacity for extreme events (56). With less margin for error, complementary strategies, such as emergency evacuation and flood-warning plans and water conservation and reallocation, become relatively more important (67). These strategies, however, incur greater residual risks to people, the consequences of which must be taken into account in a full analysis of social, economic, and environmental benefits and costs.

Desalinization

Desalination is not likely to be an important water-supply option in the United States in the next two decades. The costs of desalinating water, especially sea water, are still very high relative to most other options. However, desalination has several characteristics that make it worth considering as a supplementary source of reliable water, especially in water-short coastal cities.

Desalination plants are currently very expensive to build and operate relative to most other options. High energy costs are an especially significant constraint. However, in principle, desalination of sea water offers consumers access to an inexhaustible and noninterruptible source of supply that is free of competition for water rights (46). Desalination offers a flexible way to maintain deliveries during prolonged dry periods. It is completely independent of rainfall or of deliveries from outside the service area. When not needed, a desalination plant can be shut off, saving some operational expenses. Desalination plants can also be used in conjunction with traditional stored supplies to allow more-efficient use of these supplies during wet or normal years (e.g., more water can be drawn from a reservoir than might otherwise be safe). Incremental adjustments to the size of a plant can be made to respond to changing circumstances.

The case of the City of Santa Barbara illustrates the potential of desalination to provide flexibility during prolonged dry periods. Santa Barbara has very little groundwater and is not yet connected to the California State Water Project (SWP), so it normally relies on local surface-water sources to meet 90 to 100 percent of its 16,000-af/year water demands.[22] This reliance on local surface-water

22 B. Ferguson, City of Santa Barbara Water Department personal communication, July 1992.

sources left Santa Barbara quite vulnerable to the recent California drought. To reduce its vulnerability to future droughts, city voters-by a wide margin-approved plans to build a small ($40 million) reverse-osmosis plant to convert sea water to fresh water. Despite its cost, the city sees its desalination plant as a good way to droughtproof its water-supply system. The 7,500-af/year plant has been operational since March 1992. It was operated briefly during its commissioning period but has been on standby since local water-supply reservoirs have filled because of favorable weather conditions.

The siting of desalination plants is not as constrained to specific locations as are reservoirs. Because desalination plants occupy much less space than dams and reservoirs, it may be easier to find suitable land for them. On the other hand, desalination plants can still be sizable industrial facilities, which some find objectionablein coastal settings. In most cases, the high capital and energy costs of desalinated water constrain the near-term penetration of this technology in the United States. Brine disposal is also of some concern and may add to the long-term operating costs of such a facility.

Interregional Diversions

Over the years, many ideas have been proposed for diverting large amounts of water from water-surplus to water-deficit areas of the continent. Many plans have been proposed to bring water from the Pacific Northwest via pipelines and aqueducts to the populated regions of the Southwest. Among these have been proposals to divert water from the Columbia River, the Mississippi River, and several Canadian rivers. None of these proposals are currently being seriously considered by water planners. All are prohibitively expensive, most would likely entail unacceptable environmental impacts, and the massive quantities of water that they could supply are probably unnecessary. Politically, such projects are not now feasible. Few, if any, potential water-exporting areas are willing to give up water that may ultimately affect their growth potential or that may be needed for instream uses. Conversely, it is debatable whether additional growth should be subsidized in water-short areas, especially if there are indications that those regions could become drier as a result of climate change.

Interrgional diversions should not be ruled out completely, however. Climate change could cause a reconsideration of major diversions in the more distant future.[23] Moreover, in areas of increased precipitation, "high-flow-skimming" diversions may be attractive. Many of the existing plans are technically feasible, and although currently unlikely, some rivers now classified as wild and scenic could, in theory, be diverted. As long as other less-expensive and environmentally more sound options are available, little support of interregional diversions is likely to develop.

Reclaiming Water

Traditionally, water has been supplied to municipal residents, used, treated, and then discharged as wastewater effluent (12). Much of this wastewater could be recovered and reused where potable-quality supplies are not needed. Landscape watering, industrial cooling, groundwater recharging, and toilet flushing are among the many uses to which reclaimed water could be put. Reclaimed water could be treated to drinking-water standards at greater cost, but this may not be necessary because its use on golf courses and the like would enable high-quality water now used for these purposes to be shifted to potable uses.

The use of reclaimed water is one of the most promising new sources of water supply, especially because virtually all water uses create wastewater and, therefore, generate a reliable

[23] Note that future demographic changes in current water-surplus areas would also be an important consideration.

Box 5-J-The Use of Reclaimed Water in St. Petersburg

Freshwater supplies for the city of St. Petersburg, Florida, are limited because it is located at the end of a peninsula. The city's growing population led the Southwest Florida Water Management District to declare St. Petersburg a "water shortage area" in the early 1970s. At about the same time, the State legislature mandated that wastewater treatment plants discharging to polluted Tampa Bay start to treat their wastewater to a quality equal to that required for drinking water. St. Petersburg responded to these two actions by initiating a program to terminate disposal of wastewater into Tampa Bay and at the same time to ensure an adequate drinking supply through the year 2020 by recycling the city's wastewater (71).

Several financial, institutional, and educational barriers had to be overcome before the reclaimed-water program could be implemented. Because it proved to be too expensive to treat wastewater to potable standards, the city decided to use reclaimed water only for irrigation and industrial-cooling purposes. This required not only upgrades to existing treatment plants and storage facilities, but a new distribution system completely separate from the potable-water system. St. Petersburg was able to afford the cost of building a separate water-delivery system only because Federal (i.e., Environmental Protection Agency) and State funding was available to offset some of the planning, design, and construction costs (71).

The city had to work closely with the State Department of Environmental Regulation to write regulations that would allow for the distribution of reclaimed water, and it had to overcome initial public skepticism. A public-education campaign resulted in both acceptance and pride in the innovative program on the part of city residents.

Since 1992, St. Petersburg has had four treatment plants, which treat and chlorinate water to a high standard of quality, with all pathogens being completely removed. Approximately 10 million gallons per day (mgd)[1] of reclaimed water is routed through a separate distribution system to 7,340 customers who use the water for irrigation and cooling. The city hires inspectors to ensure that cross-connections between the two systems do not occur, but the reclaimed water is of high enough qualit y that occasional mistakes have not resulted in any adverse health effects to consumers.

The reclaimed-water treatment and distribution system has the capacity to reach 11,000 customers with potential demand of 20 mgd; the dty feels that it can reach this level of service in another 5 years. Total water demand in the city (potable and nonpotable) is approximately 42 mgd, so reclaimed water for nonpotable uses could eventually account for half of all St. Petersburg water deliveries.

By substituting reclaimed water for potable water in irrigation and cooling, the city estimates that it has eliminated the need for expansion of its potable-water-supply system until the year 2030 (59). St. Petersburg prides itself on becoming "the first major municipality in the United States to achieve zero waste-water discharge to surrounding surface waters" (71), and now receives money for water that it previously had to pay the State for permission to dump into the bay. Other communities in the United States and beyond have recognized the city's accomplishments by sending a steady stream of visitors to learn firsthand about the city's dual-distribution system.

[1] 38 million liters per day; to convert from gallons to liters, multiply by 3.785.

supply. Many communities are already using or plarming to use reclaimed water (see box 5-J), but the costs of reclaiming water are high. Moreover, costs may not decline much with advances in water-treatment technology because a major expense is for construction of separate distribution systems. Development of this new source often requires an active campaign to educate the public about the quality of reclaimed water. Compliance with environmental and health regulations is currently a major source of delay for reclamation projects, but as wastewater reclamation and reuse become more common, these delays are likely to diminish.

The Metropolitan Water District (MWD) of Southern California has sought to encourage development of wastewater reclamation facilities and to help its member agencies overcome financing problems by offering agencies $154 for each acre-foot of "new water" produced, provided that this water replaces an existing demand for imported water from MWD. Together with the $322/af it would cost local agencies to buy an equivalent amount of imported water from MWD, the subsidy makes reclamation projects economical for many local agencies.[24] MWD also finances up to 25 percent of the cost of initial feasibility studies in order to encourage consideration of reclamation possibilities. California hopes to be using 500,000 af of reclaimed water per year by 2010 (6).

Policy Options for Encouraging Structural Improvements

Option 5-19: *Require that the potential for climate change be considered in the design of new structures or the rehabilitation of old ones.* Climate change uncertainty adds another complex dimension to project scaling. Because climate could potentially change during the long lifespan of these structures, steps taken now to increase flexibility could prevent problems from developing decades in the future. In particular, the Nation's water agencies could be directed to evaluate the costs and benefits of adding additional volume, spillway capacity, or temperature controls to existing or new structures.

Option 5-20: *Appropriate funds for wastewater reclamation, desalination, or other water-supply research.* Congress could consider using the authority of sections 106 and 108 of the Water Resources Research Act of 1984.

FIRST STEPS

Water resource management has two essential objectives: to ensure that enough water of adequate quality is available during normal and drought periods for all necessary demands--including environmental ones-and to ensure that water in the form of life- and property-threatening floods does not get out of control. Growing stress on water resource systems and the possibility that new stresses such as climate change will arise make these objectives increasingly difficult to accomplish. The demand- and supply-management options discussed in this chapter (table 5-4) are likely to be increasingly important as means to cope with growing stress on water supplies. These options contribute greater flexibility, greater efficiency, or both to water resource management and thus aid, generally, adaptation to climate change.

Considering climate change alone, there are no compelling arguments why any one supply- or demand-management option should be preferred to another. All are important and would contribute, if sometimes only in small ways, to improved water resource management in a changed climate. However, the system is very inefficient now, given numerous institutional obstacles, lack of incentives to conserve water, overlapping and sometimes conflicting responsibilities of Federal agencies, and lack of coordination among levels of government. Fundamental changes are needed in the way water is valued and used; those changes can begin with steps that both relieve existing stresses and make sense for climate change. Implementing the suggestions below—drawn from the whole range of options discussed above-would likely create the conditions for future progress in water resource planning and management.

- **Improve extreme-events management.** Perhaps the most important actions that should not be delayed concern improving the management of extreme events. Floods and droughts will continue to occur even if they cannot be linked definitively to climate change. Improving flood and drought management now could help minimize both near-and long-term losses. Important first

[24] D. Adams, Director of Resources, Metropolitan Water District of Southern California, Los Angeles, personal communication, July 1992.

Table 91-Summary of Options to Improve Water Resource Management

Institutional	
	Resurrect the former Water Resources Council
	Reestablish and strengthen Federal-State river basin commissions
	Create an interagency task force to develop a national drought policy
	Create a national flood-assessment board
	Integrate floodplan management into basin-scale planning
Research and development	
	Fund the development and use of water-conservation technologies
	Fund the development and use of waste-water-reclamation technology
	Increase funding for development and promotion of new analytic tools
	Incorporate flexibility into the design of new structures or the rehabilitation of old ones
Direct Federal levers	
	Revise the tax code to promote conservation investment
	Provide stronger leadership to facilitate water transfers
	Clarify reclamation law on trades and transfers
	Reduce Federal obstacles to Interstate transfers
	Clarify the rules regarding the marketing of Indian water
	Allow Federal agencies to buy water for environmental purposes
	Expand the scope and/or nature of the Western Water Policy Review
	Conduct post-drought audits
	Direct the Interagency floodplain Management Task Force to promote the preparation of State floodplain management plans
Economic Incentives and disincentives	
	Allow state revolving-loan funds to be used for conservation investments
	Reform pricing in Federal water projects
	Tie funding of State water projects to adoption of Improved water-management practices
	Encourage adoption of risk-management and -minimization practics to mitgate drought effects
Operational	
	Encourage water conservation in Federal facilities
	Require operating agencies to undertake periodic audits to Improve efficiency
	Give Federal operating agencies greater ability to modify project operations to meet changing conditions

a An order of priority has not been established.

SOURCE: Office of Technology Assessment 1993.

steps could be for Congress to direct the executive branch to create an interagency drought task force with authority to develop a national drought policy and, similarly, a national flood-assessment board to establish national goals for floodplain management. Title V of H.R. 62, the National Flood Insurance Compliance, Mitigation, and Erosion Management Act of 1993, establishes a flood-insurance task force. This bill could be broadened to create a more comprehensive flood-assessment board. The President could establish an interagency drought task force without additional authority, but Congress may wish to direct the Administration to do so.

- Promote management of reservoirs on a basin-wide level. Operation of reservoirs within the same basin as a single system rather than individually, as is often the case, could greatly improve the efficiency and flexibility of water-quantity management. Making such operations easier would also assist development of the more integrated approach desirable for managing water quality, wetlands, flooding, and drought. New legislation, perhaps as part of the next omnibus water bill, could grant the Army Corps of Engineers and the Bureau of Reclamation greater administrative flexibility to do this.

- **Promote water marketing.** Among many institutional problems that Congress may wish to consider are those related to water marketing. As long as adequate attention is given to protecting third-party interests, water markets could provide an efficient and flexible means of adapting to various stresses, including a changing climate. Of the several options identified in this report for reducing impediments to creating water markets, early action to clarify reclamation law on trades and transfers and to define the Federal Government's interest in facilitating the creation of markets would be most useful. Congress could urge the Department of the Interior to provide stronger leadership to assist transfers. Evaluation of water marketing should also be thoroughly considered in the Western Water Policy Review, authorized in late 1992 by P.L. 102-575, the Central Wiley Project Improvement Act.
- **Promote use of new analytical tools.** Further development, dissemination, and use of new modeling and forecasting tools could greatly assist water resource management. Some current development efforts (e.g., NOAA's WHS initiative) have not been adequately funded, and the most advanced tools now available are not yet being used by many States or water utilities. Small sums spent now promoting dissemination and use of these tools could save substantial sums later. Section 22 of the Water Resources Development Act of 1974 authorizes funding for training and technical assistance to States and could be used to promote use of analytical tools. Congress may also want to consider providing funds to develop or refine tools that incorporate climate uncertainty into traditional hydrologic analyses.
- **Promote demand management.** Several "targets of opportunity" for improving water-use efficiency are likely to present themselves in the 103d Congress. The upcoming reauthorization of the Clean Water Act stands out. State revolving funds (created under Title VI of the act) have been a successful means for funding wastewater treatment plants. In CWA reauthorization, Congress could consider making conservation projects eligible for revolving-fund loans. This would not only promote demand management but would reduce the amount of water that needs treating. The Federal Government could also make a contribution to promoting efficient water-use practices by setting an example in its own numerous facilities. The Energy Policy Act of 1992 proposes just this but concentrates primarily on energy conservation rather than water conservation. A technical-adjustment bill to the Energy Policy Act may be considered in the 103d Congress and would provide a way to clarify and underline congressional intent toward water conservation in Federal facilities.
- **Expand the scope of the Western Water Policy Review.** With the enactment of Title XXX of the Reclamation Projects Authorization and Adjustment Act of 1992 (P.L. 102-575), Congress authorized the President to oversee a major water-policy study. Under the heading Western Water Policy Review, Title XXX directs the President to undertake a comprehensive review of Federal activities in the 19 Western States that affect the allocation and use of water resources and to make a report to appropriate congressional committees by the end of October 1995 (87).

Congress has authorized or undertaken more than 20 major studies since 1900 to provide a basis for improving national policies that affect water management. Some have led to important changes in policy; others have been largely ignored. Despite the uneven record of these studies, a new study is warranted: two decades have lapsed and many demographic, economic, environmental, and attitudinal changes have occurred since the last comprehensive study of water resource problems was completed by the presidentially appointed National Water Commission (NWC) in 1973. Some of the areas that need detailed attention now include demand management, quality-vs.-quantity issues, instream-water values, social and environmental impacts, water marketing and pricing, land use in relation to water resources, cost sharing and upfront financing, comprehensive urban water planning, ways to promote integrated river basin planning, and development of analytical tools. Climate change is not mentioned as a factor motivating the Western Water Policy Review, but the study could provide an opportunity to assess more fully how climate change may affect water resources and to evaluate policy options that might help with adaptation to a warmer climate.

Congress could expand the scope and/or nature of the Western Water Policy Review. Water problems are not all in the West, so a more general review of national water policy may make sense. Expanding the currently authorized study would, however, greatly increase its complexity. Also, other committees of Congress may want to become involved, and broader State or regional representation would probably be required. Broadening the study could be accomplished by amending the legislation or by Executive Order. If the Western Water Policy Review is not expanded to include the entire United States, Congress could authorize a similar follow-on study of eastem water issues.

The Western Water Policy Review may also provide an opportunity to explicitly consider land-use practices and water resource issues jointly. One shortcoming of most previous water-policy studies is that land and water use were not considered together. However, the relationship between the two is a close one, and there appear to be significant opportunities to improve both water-quantity and water-quality management by improving land-use practices. Fur-

WATER-FIRST STEPS

- **Improve extreme-events management**
  - Direct the executive branch to create an interagency drought task force with authority to develop a national drought policy.
  - Direct the executive branch to create a national flood assessment board to establish national goals for floodplain management.
- **Promote management of reservoirs on a bssin-wide level**
  - --Grant the Bureau of Reclamation and the Army Corps of Engineers greater administrative flexibility to manage reservoirs basin-wide in the next 1994 Omnibus Water Bill.
- **Promote water marketing**
  - --Clarify reclamation law on trades and transfers
  - -Urge the Department of the interior to provide stronger leadership to assist transfers.
  - --Require evaluation of water marketing in the Western Water Policy Review, authorized by P.L 102-575.
- **Promote use** of new analytical tools for water modelling and forecasting
  - -Use funds under Section 22 of the Water Resources Development Act of 1974 to promote use of analytical tools as part of the training and technical assistance to States.
- **Promote demand management**
  - --Make conswvation projects eligible for revolving-fund loans in the Clean Water Act reauthorization.
  - -Clarify the stated congressional intent of promoting water conservation in Federal facilities with a technical-adjustment bill to the Energy Policy Act of 1992 (P.L 102-486).
- Expand **the scope of the Western Water Policy Review**
  - --Evaluate land-use practices and water resource issues jointly.
  - --Include an analysis of the eastern States now or authorize their study after the western review is completed.

thermore, any study focused exclusively on water resources might fall short of providing a basis for coping with all of the problems that could arise if climate changes.

CHAPTER 5 REFERENCES

1. Anonymous, 'Sacramento River Fisheries: Restoring a Declining Resource," *Western Water*, July/August, 1990.
2. Anonymous, "The Greening of the Corps?" *SFI Bulletin* (Sport Fishing Institute), No. 434, May 1992.
3. Ante@ W., "Implementing ASCE Water Conservation Policy," in: *Water Resources Planning and Management: Proceedings of the Water Resources Sessions at Water Forum '92*, Water Forum '92, Baltimore, MD, Aug. 2-6, 1992.
4. Beecher, J., and A. Laubach, *Compendium on Water Supply, Drought, and Conservation* (Columbus, OH: The National Regulatory Research Institute, 1989),
5. Burby, R., et al., *Action Agenda for Managing the Nation's Floodplains, Special* Publication 25 (Boulder, CO: Natural Hazards Research and Applications Information Center, University of Colorado, 1992).
6. California Department of Water Resources, *California Water: Looting to the Future*, Bulletin 160-87, November 1987.
7. California Department of Water Resources, 'The 1991 Drought Water Bank,'' January 1992.
8. Chahine, M., "l'he Hydrological Cycle and Its Influence on Climate," *Nature*, vol. *359*, Oct. 1, 1992.
9. Colorado River Board of California, *Conceptual Approach for Reaching Basin States Agreement on Interim Operation of Colorado River System Reservoirs, California's Use of Colorado River Water Above Its Basic Apportionment, and Implementation of an interstate Water Bank*, 1991.
10. Dowd, R., "The Superfund Impasse," *Environmental Science and Technology*, vol. *22, No. 8, 1988.*
11. *Environmental* and Energy Study Institute, *1993 Briefing Book on Environmental and Energy Legislation* (Washington, DC: EESI, 1993)0
12. Flack, J., "Increasing Efficiency of Nonagricultural Water Use," in: *Water Scarcity: Impacts on Western Agriculture*, E.A. Engelbert and A.F. Scheuring (eds.)(Berkeley, CA: University of California Press, 1984), p. 133.
13. Foster, C., and P. Rogers, "Federal Water Policy: Toward an Agenda for Action,'' discussion paper, John F. Kennedy School of Government, Harvard University, Cambridge, MA, August 1988.
14. Foxworthy, B., and D. Moody, "National Perspective on Surface Water Resources," in: *National Water Summary 1985—Hydrologic Events and Surface-Water Resources*, U.S. Geological Survey Water-Supply Paper 2300 (Washington, DC: U.S. Government Printing Office, 1986).
15. Frederick, K., "Overview, '' in: *Scarce Water and Institutional Change*, K. Frederick (ed.)(Washington, DC: Resources for the Future, 1986),
16. Frederick, K., "Assessing the Impacts of Climate Change on Water Scarcity," discussion paper, Resources for the Future, Washington, DC, 1991.
17. Frederick, K., "Balancing Water Demands with supplies: The Role of Demand Management in a World of Increasing Scarcity," report prepared for the International Bank for Reconstruction and Development, Washington, DC, May 1992.
18, Frederick, K., and P. Gleick, "Water Resources and Climate Change," in: *Greenhouse Warming: Abatement and Adaptation*, N. Rosenberg, W. Easterling, P. Crosson, and J. Darmstadter (eds.)(Washington, DC: Resources for the Future, 1988), p. 141.
19. Fulton, N., "Reducing the Risks: The Need for Comprehensive Flood Damage Reduction Policies," in: M. Reuss (cd.) *Water Resources Administration in the United States: Policy, Practice, and Emerging Issues (Lansing, MI: Michigan State* University Press, 1993).
20. Garner, E., and J. Weis, "Coping with Shortages: Managing Water in the 1990s and Beyond,'' *Natural Resources and Environment, vol. 5, No. 4, spring* 1991, p, 63.
21. Getches, D., ''Indian Water Marketing: A Source of Economic and Cultural Survival,'' *Water Science and Technology Board Newsletter*, National Research Council, vol. 10, No. 1, January 1993.
22. Gibbons, D., *The Economic Value of Water* (Washington, *DC: Resources* for the Future, 1986).
23. Gillilan, D., "Innovative Approaches to Water Resource Management,'' contractor report prepared for the Office of Technology Assessment, September 1992.
24. Glantz, H.M. (cd.), *Societal Responses to Regional Climate Change: Forecasting by Analogy* (Boulder, CO: Westview Press, 1988).
25. Gleick, P., "Vulnerability of Water Systems," in: *Climate Change and U.S. Water Resources (New York:* John Wiley and sons, 1990),
26. Gleick, P. (cd.), *The Colorado River Basin and the Greenhouse Effect: Water Resources and Water Management* (Berkeley, *CA:* Pacific Institute for Studies in Development, Environment, and Security, 1990).
27. Hanchey, J., K. Schilling, and E. Stakhiv, ''Water Resources Planning Under Climate Uncertainty,'' in: *Proceedings Of the First North American Conference on Preparing for Climate Change: A Cooperative Appoach* (Washington, *DC: The Climate* Institute, 1987), p. 396.
28. Hirschboeck, K., "Climate and Floods," in: *National Water Summary 1988-8%-Hydrologic Events and Floods and Droughts*, U.S. Geological Survey Water-Supply Paper 2375 (Washington, DC: U.S. Government Printing Office, 1991).
29. Holburt, M., R. Atwater, and T, Quinn, ''Water Marketing in Southern California,'' *Journal of the American Water Resources Association*, vol. 80, No. 3, March 1988.
30. Howitt, R, N. Moore, and R. Smith, "A Retrospective on California's 1991 Emergency Drought Water Bank,'' report prepared for the California Department of Water Resources, March 1992.
31. Intergovernmental Panel on Climate Change, Response Strategies Working Group, *Strategies for Adaption* to *Sea Level Rise (The Hague, The Netherlands: Ministry* of Transport and Public works, 1990).
32. Intergovernmental Panel on climate Change (IPCC), 1992 *IPCC Supplement (WCC*, February 1992).

33. Jacoby, H., "Water Quality," in: *Climate Change and U.S. Wafer Resources,* P. Waggoner (cd.)(New York: John Wiley and Sons, 1990).

34. Kellogg, W., and Z. Zhao, "Sensitivity of Soil Moisture to Doubling of Carbon Dioxide in Climate Model Experiments. Part I: North America,'' *Journal of Climate,* vol. 1, No. 4, April 1988.

35. Kennedy, D., "Political and Institutional Constraints of Responding to Climate Change, ' paper presented at the First National Conference on Climate Change and Water Resources Management, Albuquerque, NM, Nov. 5-7, 1991.

36. Knopman, D., and R. Smith, "20 Years of the Clean Water Act," *Environment,* January/February 1993.

37. Koellner, W., "Climate Friability and the Mississippi River Navigation System, in: *Societal Responses to Regional Climatic Change:' Forecasting by Analogy,* M.H. Glantz (ed.)(Boulder, CO: Westview Press, 1988), p. 275.

38. Larson, L., "Floodplain Management: The Gap Between Policy and Implementation or Principle and Practice, " *Water Resources Update, No. 90,* winter 1993.

39. Laurine, D., and L. Brazil, "Pilot Project Results from a Probability Based Long Range Water Management/Supply Forecast,'' National Oceanic and Atmospheric Admihistration, National Weather Service, Salt Lake City, UT, 1993.

40. Lettenmaier, D., 'T. Gan, and D. Dawdy, "Interpretation of Hydrologic Effects of Climate Change in the Sacramento-San Joaquin River Basin, California, " in: *The Potential Effects of Global Climate Change on the United States (Appendix A: Water Resources),* J. Smith and D. Tirpak (eds.)(Washington, DC: U.S. Environmental Protection Agency, 1989).

41. Levels Reference Study Board, International Joint Commission, ''Finat Report of CCC GCM 2 X $C0_2$ Hydrological Impacts on the Great Lakes" (Hanover, NH: Levels Reference Study Board, December, 1991).

42. McDonnell, L., R. Wahl, and B. Driver, *Facilitating Voluntary Transfers of Bureau of Reclamation-Supplied Water, Volumes 1 and 2* (Boulder, CO: Natural Resources Law Center, University of Colorado School of Law, 1991).

43. Mearns, L., "Implications of Global Warming for Climate Variability and the Occurrence of Extreme Climate Events, " in *Drought Assessment, Management, and Planning: Theory and Case Studies,* D. Wilhite (ed.)(Boston, MA: Kluwer Academic Publishers, 1993).

44. Metropolitan Water District, *The Regional Urban Water Management Plan for the Metropolitan Water District of Southern California,* prepared by Planning and Management Consultants, Ltd., Carbondale, IL, November 1990.

45. Miller, B., et al., *Sensitivity of the TVA Reservoir and Power Supply Systems to Extreme Meteorology* (Noms, TN: TVA Engineering Laboratory, 1992).

46. Miller, H., City Council Member, Santa Barbara, CA, te@rnony at hearings before the Senate Environment and Public Works Committee onS.481, the Water Research Act of 1991, July 23, 1991.

47. Miller, K., "Hydropower, Water Institutions, and Climate Change: A Snake River Case Study," *Water Resources Development,* vol. *5, No. 2,* June 1989.

48. Moreau, D., "It Will Be a Long Wait for Roof," paper presented at the 1992 Southeast Climate Symposium, Changing Climate and Water Resources, University of Charleston, Charleston, SC, Oct. 27-29, 1992.

49. National Regulatory Research Institute, *Compendium on Water Supply, Drought, and Conservation,* NRRI *89-15* (Columbus, OH: National Regulatory Research Institute, October 1989).

50. National Research Council, *Water Transfers in the West: Efficiency, Equity, and the Environment* (Washington, *DC:* National Academy Press, 1992).

51. National Research Council (NRC), *The Global Climate Change Response Program of the Bureau of Reclamation: A Mid-Course Evaluation (Washington DC: NRC, 1992).*

52. Regier, H., and J. Meisner, "Anticipated Effects of Climate Change on Freshwater Fishes and Their Habitat,'' *Fisheries,* vol. 15, No. 6, November-December, 1990, p. 11.

53. Reisner, M., *Cadillac Desert: The American West and Its Disappearing Water (New* York: Viking Penguin, Inc., 1986).

54. Reisner, M., and S. Bates, *Overtapped Oasis: Reform or Revolution for Western Water (Washington DC:* Island Press, 1990).

55. Reuters Ltd., "Midwest Levees Straining: Mississippi River Continues to Rise," *Washington Post,* July *8, 1993,* p. A3.

56. Riebsame, W., ''Anthropogenic Climate Change and a New Paradigm of Natural Resource Planning," *Professional Geographer, vol. 42, No. 1,* 1990, pp. 1-12.

57. Riebsame, W., S. Changnon, and T. Karl, *Drought and Natural Resources Management in the United States: Impacts and Implications of the 1987-89 Drought* (Boulder, CO: Westview Press, 1991).

58. Rind, D., et al. "Potential Evapotranspiration and the Likelihood of Future Drought,'' *Journal of Geophysical Research, vol. 95, No. D7,* June 20, 1990.

59. Rocky Mountain Institute, *Water Efficiency: A Resource for Utility Managers, Community Planners, and Other Decision-makers, in* cooperation with the U.S. Environmental Protection Agency Office of Water (Snowmass, CO: Rocky Mountain Institute, 1991),

60. Rogers, P., "What Water Managers and Planners Need to Know about climate Change and Water Resources Management, ' paper presented at the First National Conference on Climate Change and Water Resources Management, Albuquerque, NM, Nov. 5-71991.

61. Schmandt, J., and G. Ward, *Texas and Global Warming: Water Supply and Demand in Four Hydrological Regions (The* University of Texas at Austin: Lyndon Baines Johnson School of Public Affairs, 1991).

62. Schneider, S., P. Gleick, and L. Mearns, ''Prospects for Climate Change," in: *Climate Change and U.S. Water Resources,* P. Waggoner (ed.)(New York: John Wiley and Sons, 1990), p. 63.

63. Sheer, D., ''Managing Water Supplies to Increase Water Availability, " in: *National Water Summary 1985-Hydrologic Events and Surface-Water Resources,* U.S. *Geological Survey* Water-Supply Paper 2300 (Washington DC: U.S. Government Printing Office, 1986).

64. Sheer, D., "Reservoir and Water Resources Systems in the Face of Global Climate Change," contractor report prepared for the Office of Technology Assessment, December 1992.

65. Smith, R.T., *Trading Water: An Economic and Legal Framework for Water Marketing* (Washington, DC: The Council of State Policy and Planning Agencies, 1988).

66. Solley, W., R. Pierce, and H. Perlman, *Estimated Use of Water in the United States in 1990,* USGS Survey Circular 1081 (Washington, DC: U.S. Geological Survey, 1993).

67. Stakhiv, E., and J. Hanchey, "policy Implications of Climate Change" report of the First U.S.-Canada Symposium on Impacts of Climate Change on the Great Lakes Basin, Oak Brook, IL, Sept 27-29, 1988 (January 1989).

68. Stegner, W., *The American West as Living Space* (Ann Arbor, MI: University of Michigan Press, 1987).

69. Stone, W., M. Minnis, and E. Trotter (eds.), *The Rio Grande Basin: Global Climate Change Scenarios,* New Mexico Water Resources Research Institute Report No. M24, June 1991.

70. Tarlock, A.D., "Western Water Law, Global Warming, and Growth Limitations," *Loyola Of Los Angeles Law Review,* vol. 24, No. *4,* June 1991, p. 999.

71. Towry, J., and D. Shulmister, "Water Conservation Pioneers," *Quality Cities '90, May 1990.*

72. Us. Advisory Commission on Intergovernmental Relations (ACIR), *Coordinating Water Resources in the Federal System: The Groundwater-Surface Water Connection* (Washington, *DC:* ACIR, October 1991).

73. U.S. Army Corps of Engineers, *IWR-MAIN Water Use Forecasting System Version 5.1* (Fort Belvoir, VA: U.S. Army, Institute for Water Resources, 1988).

74. Us. Army corps of Engineers., *The National Study of Water Management During Drought: Report of the First Year of Study* (Fort Belvoir, VA: U.S. Army, Institute for Water Resources, 1991),

75. U.S. Army Corps of Engineers, *U.S. Army Corps of Engineers Emergency Water Planning: A Program Evaluation* (Fort Belvoir, VA: U.S. Army, Institute for Water Resources, 1992).

76. U.S. Army Corps Engineers, *Volume III, Summary of Water Rights—State Laws and Administrative Procedures,* report prepared for U.S. Army, Institute for Water Resources, by Apogee Research, Inc., June 1992.

77. U.S. Congress, Office of Technology Assessment *Energy Efficiency in the Federal Government: Government by Good Example?* OTA-E-492 (Washington, *DC:* U.S. Government Printing OffIce, May 1991).

78. U.S. Congress, Subcommittee on Technology and National Security of the Joint Economic Committee, *Demographic Change and the Economy of the Nineties* (Washington DC: U.S. Government Printing Office, 1991).

79. U.S. Department of Agriculture, Forest Service, "RPA Assessment of the Forest and Rangeland Situation in the United States, 1989," Forest Resource Report No. *26,* October 1989.

80. U.S. Environmental Protection Agency (EPA), *The Potential Effects of Global Climate Change on the United* States, EPA-230-05-89-050, December 1989.

81. U.S. Environmental protection Agency (EPA), *Incentive Analysis for Clean Water Act Reauthor-ization: Point Source/Nonpoint Source Trading for Nutrient Discharge Reductions,* prepared *by* Agogee Research, Inc. (Washington, DC: EPA, 1992).

82. U.S. Environmental Protection Agency (EPA), *The Watershed Protection Approach: Annual Report 1992,* EPA840-S-93-001 (Washington, DC: EPA, January 1993).

83. U.S. Geological Survey, *National Water Summary 1985—Hydrologic Events and Surface WaterResources,* Water-Supply Paper 2300 (Washington DC: U.S. Government Printing Office, 1986).

84. U.S. Geological Survey, *National Water Summary 1986—Hydrologic Events and Ground-Water Quality,* Water-Supply Paper 2325 (Washington DC: U.S. Government Printing Office, 1988).

85. U.S. Geological Survey, *National Water Summary 1987—Hydrologic Events and Water Supply and Use,* Water-Supply Paper 2350 (Washington, DC: U.S. Government Printing Office, 1990).

86. U.S. Geological Survey, *National Water Summary 1988-8% Hydrologic Events and Floods and Droughts,* Water-Supply Paper 2375 (Washington, DC: U.S. Government Printing office, 1991).

87. U.S. House of Representatives, *Reclamation Projects Authori-ration and Adjustment Act of 1992—Conference Report,* Report 102-1016 (Title XXXIV: Central Valley Project Improvement Act; Title XXX: Western Water Policy Review), Oct. 5, 1992.

88. U.S. Water Resources Council (WRC), *The Nation's Water Resources 1975-2000, Volume 2: Water Quantity and Related Land Considerations (Washington, DC: WRC, 1978).*

89. Wade Miller Associates, *The Nation' sPublic Works: Report on Water Supply* (Washington, *DC:* National Council on Public Works Improvement, May 1987).

90. Waggoner, P., and J. Shefter, *Climate Change and U.S. Water Resources,* P. Waggoner (ed.)(New York: John Wiley and Sons, 1990).

91. Wahl, R., *Markets for Federal Water: Subsidies, Property Rights, and the Bureau of Reclamation* (Washington, DC: *Resources* for the Future, 1989).

92. Wahl, R., "The Management of Water Resources in the Western U.S. and Potential Climate Change," contractor report prepared for the OffIce of Technology Assessment October 1992.

93. Wallace, M., "Indian Water Rights Settlements," paper presented at the Office of Technology Assessm ent workshop on Western Lands, Boulder, CO, July 23, 1992.

94. Water Quality 2000, A *National Agenda for the 21st Century* (Alexandria, VA: Water Quality 2000, Water Environment Federation, 1992).

95. Werick, W., "National Study of Water Management During Drought: Results Oriented Water Resources Management," paper presented at the 20th Anniversary Conference of the Water Resources Planning and Management Division of the American Society of Civil Engineers, Seattle, WA, May 3-5, 1993.

%. Western Governors' Association *Water Efficiency: Opportunities for Action (Denver, CO:* Water Efficiency Working Group, 1987).

97. We-stern States Water Council, ''Interregional Water Transfers,' a report requested by the Nevada State Legislature, May 1991. From remarks by former Arizona Governor Bruce Babbitt before the Seventh Annual We-stem States Water Council Water Management Symposium in Scottsdale, AZ, Oct. 10, 1990.
98. White, D., D. Collins, and M. Howden, "Drought in Australia: Prediction, Monitoring, Management, and Policy," in: *DroughtAssessment, Management, and Planning: Theory and Case Studies* (Boston, MA: Kluwer Academic Publishers, 1993).
99. Wilhite, D., ''Drought,'' in: *Encyclopedia of Earth System Science, Volume 2 (New* York: Academic Press, Inc., 1992),
100. Wilhite, D., "Drought Management and Climate Change, " contractor report prepared for the Office of Technology Assessment, December 1992,
101. Wilhite, D., N. Rosenberg, and M. Glantz, 'Improving Federal Response to Drought,'' *Journal of Climate and Applied Meteorology,* vol. 10, 1986.
102. Wingerd, D., and M. Tseng, ' 'Flood and Drought Functions of the U.S. Army Corps of Engineers, " in: *National Water summary 1988-89—Hydrologic Events and Floods and Droughts,* U.S. Geological Survey Water-Supply Paper 2375 (Washington DC: U.S. Government Printing Office, 1991).
103. Wright, J., and D. porter, ''Floodplain Management and Natural Systems," paper presented at the National Forum on Water Management Policy, American Water Resources Association, Washington DC, 1992.

APPENDIX 5.1–WATER RESOURCE CONCERNS: REGION BY REGION AND STATE BY STATE

New England Region

Development of surface and groundwater is substantial here. Municipal and *industrial pollution is localized. Drought is rare. The lack of redundancy of water supplies indicates vulnerability.*

Connecticut--Small reservoirs susceptible to below-average rainfall are networked with larger, robust reservoirs; point and non-point contamination; potential flooding due to convective storms in the summer, hurricanes in the fall, and snowmelt in the spring.

Main--Abundant water resources; localized groundwater pollution due to urbanization agriculture, and industrial-municipal waste; saltwater intrusion potential in coastal areas with high groundwater withdrawals; drought rare, but characterized by low stream flows, low groundwater levels, and high forest-fire risk 20 percent of Maine's electricity is derived from hydropower flooding possible during spring snowmelt.

Massachusetts-plentiful water resources, but not well-distributed in proportion to population density (large cities in the east and reservoirs in the west); quality of certain supply lakes and reservoirs threatened by high sodium concentrations; Boston supply particularly susceptible to drought; potential widespread flooding caused by spring snowmelt with rain and tropical storms.

New Hampshire-Abundant water resources; summer stream flows and groundwater supplies rely on seasonal snowmelt tourism-recreation industry dependent on water resources; regional drought rare, but droughts do affect public water supply occasionallly, possible flooding due to spring snowmelt tropical storms, ice jams, and intense thunderstorms.

Rhode Island--Generally sufficient water supply; most feasible supplies already developed and groundwater pumped at capacity, so redistribution possibly ncessary to meet future water demand; coastal aquifers and reservoirs endangered by saltwater intrusion others endangered by contamination wetlands (10 to 30 percent of the State) susceptible to prolonged drought potential flooding due to convective storms, tropical storms, and snowmelt with rainfall.

Vermont—Abundant water resources of generally good quality; some localized groundwater contamination in areas of high population density, severe drought rare, but even short droughts can affect agriculture and livestock-public supply storage capacity provides l-year buffer, flooding potential from tropical storms, intense frontal systems, or snowmelt with rainfall,

Mid-Atlantic Region

Water supply is becoming an issue in some metropolitan areas, saltwater intrusion is occurring along coasts, and industrial and municipal pollution is an issue.

Delaware--Municipal and industrial usage causing increased water-supply pressure in heavily populated regions; peak usage coincides with low-flow periods, causing capacity problems; Dover relies exclusively on groundwater in a region subject to overdraft (northernmost and central Delaware); saltwater intrusion in coastal areas; toxics in the sediments, water column, and biota of Delaware estuary, but improving, regional flooding potential due to tropical storms and local flooding by convective storm.

Maryland--Water supply well-managed for heavy reliance on surface water, drought stresses domestic supply, groundwater use on coastal plain subject to saltwater intrusion; point and non-point pollution; Hurricanes and convective storms potentially cause floods.

New Jersey-surface water in New Jersey wed extensively, but supply development outpaced by demand, making drought dangerous; surface-water quality threatened by agricultural runoff and industrial-municipal dischharge as well as saltwater intrusion in coastal areas; groundwater quality threatened by toxins (l,224 known or suspected hazardous waste sites in 1986); potential flooding due to frontal systems and tropical and convective storms.

New York-Demand in New York City significantly exceeds safe yield; Long Island depends solely on aquifers susceptible to saltwater intrusion and drought historic water rights create competition and restrict reallocation non-point sources of pollution threaten surface and groundwater quality in several areas; toxic plumes from inactive hazardous waste sites are mobilized by increased precipitation; sea level rise would affect the New York City and Long Island metropolitan areas and the lower Hudson River estuary (Poughkeepsie supply intake and New York City emergency pumping station); potential regional flooding from frontal systems, spring snowmelt, and tropical storms, local flooding due to convective storms.

Pennsylva nia-Water supply potentially a critical problem; although supply is adequate under normal conditions, drought causes problems, especially for smaller supply systems; quality of surface and groundwatar jeopardized by drainage from coal-mining areas and non-point sources in agricultural areas, all compounded by acid precipitation convective storms, tropical storms, rain on frozen ground or snow pack, and ice jams all potential instigators of flooding.

Virginia--Considered to be a water-rich state; still, some community-supply systems face insufficient capacity (especially along the southeastern coast); saltwater intrusion potential in coastal areas; localized pollution of surface and groundwater, possible flooding caused by tropical and convective storms.

South Atlantic Region

Here, the use of available water ***resources is increasing, and municipal and industria 1 development causes shortages in some cities.***

Alabama-Abundant water resoume& some highly industrialized areas risk shortages during drought if development continues; localized groundwater contamination due to mine-tailing leaching. saltwater intrusion, and waste sites; potential flooding due to tropical storms or hurricanes and frontal systems.

Florida --State's water resources are a source of competition between municipal, industrial environmental and recreational uses; population pressure in some areas; coastal aquifers **subject to saltwater intrusion, so sea** level rise would reduce safe yield; need for increased storage capacity western and southwestern Florida particularly vulnerable to drought sensitive ecosystems and brackish water subject to flooding; Everglades National Park is entirely below the 8.5-foot (2.5-meter)[1] contour, 34 percent below l-foot contour majority of population lives on coastlines, very low elevation so sea level rise could be devastating, frequent flooding usually along the coast due to hurricane and tropical-storm surges; most thunderstorms per year in the Nation

Georgia-Surface water extensively used in the northern parts of the State and groundwater in the south; high-growth areas with increasing municipal, industrial environmental, and downstream-"requirements susceptible to drought; saltwater encroachment on coastal aquifers (would be exacerbated by sea level rise); competition for water stored in major reserving groundwater overdraft in southwestern corner due to agriculture; potential flooding due to frontal systems, convective storms, tropical storms and hurricanes.

North Carolina--Abundant,water resources some areas approaching limits of available supply; localized pollution by toxins, nutrients, and sediments; flooding and coastal erosion potential, saltwater intrusion from sea level rise, drought impacts agricultural and domestic use, exacerbates increasing competition for water regional flooding potential associated with tropical storms and hurricanes.

South Carolina --Plentiful water resources; need management and coordination of surface and groundwater resources; quality generally good, some nutrient, dissolved oxygen, saltwater intrusion and suspended solids problems locally, development pressure on wetlands; potential flooding caused by hurricanes, tropical storms, and thunderstorms.

Lower Mississippi Basin

Water supplies here for medium- to small-sizedcomntuni$aare vulnerable to drought, and industrial pollution on and salinity present problems.

Arkansas-Abundant water resoures dissolved solids sediment and saltwater intrusion in the southeast comer restrict use in some areas; **groundwater overdraft in some areas; agriculture susceptible to drought;** possible flooding from tropical and convective storms.

Louisiana—Water resources for municipal and indusdtrial supply, agriculture, navigation, environmental uses, and recreation; due to reliance on rain and shallow water tables, even short droughts greatly affect agriculture; coastal erosion, loss of marshes, and subsidence claim large amounts of state land annually, more than half of the state is a floodplain so hurricanes and tropical storms, convective storms, or upstream events can endanger large parts of State.

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[1] To convert feet to meters, multiply by 0.305.

Mississippi-Abundant water resources; agricultural base of the State economy (and catfish farming) creates large drought risk (1988 drought was devastating); saltwater intrusion of aquifers; desire to tap into Tennessee and Tombigbee Rivers for more supply; potential flooding due to frontal systems in the winter and hurricanes and tropical storms in the summer.

Ohio River Basin

Municipal water supplies fir median-and small-sized communities and Ohio River flows are vulnerable to drought here.

Indiana--Abundant water resources; self-supplied industry is the major user; quality problems downstream from municipal and industrial discharge points; low flows of drought hamper navigation on Ohio River possible flooding from frontal systems, convective storms, and rain with snowmelt.

Kentucky--Abundant water resourccs during most of the year, seasonal and areal variation; competition between municipal water supply and irrigated agriculture during low flows; coal mining oil and gas operations, agriculture and domestic waste discharge adversely affect water quality; agricultural loss and forest-fire danger during drought; possible flooding from frontal systems and convective storms.

Ohio-Ample surface-water supplies; municipal supply for medium-sized communities fragile during drought agricultural runoff, sedimentation, mining, and hazardous-waste-disposal sites create quality problems; instream flows for navigation are an important consideration during drought despite public works, floods from frontal systems and convective storms affect the State every year.

Tennessee--Generally considered a water-rich State, but limitations visible during drought; smaller supply systems of eastern Tenessee susceptible to drought non-point-source pollution and toxic-waste sites affect quality of surface waters; low dissolved-oxygen concentrations in reservoir releases; localized groundwater contamination some localized overdraft during drought; hydroelectric-power generation at 24 dams susceptible to drought thermal-power generation suffers from increased surface water temperatures during low flows; lack of irrigation infrastructure stresses agriculture during drought; flooding potential due to frontal systems and thunderstorms greatly mitigated by flood-control works.

West Virginia--Abundant water resources; some localized water-quality problems due to non-point sources such as manufacturing, municipal waste, coal mines, and farms; drought not a major concern, but potential flooding of flat and narrow valley floors due to frontal systems and cyclonic and convective storms is a major problem.

Upper Great Lakes-Upper Mississippi Basin Region

Management of the Mississippi and Missouri River systems is difficult during drought. Additional problem arise as a result of fluctuating Great Lakes levels and of impacts on water quality. The heavy chemical and biological loading of the upper Mississippi due to industrial, municipal, and agricultural pollution is a problem.

Illinois-Abundant water resources; self-supplied industry is major user; small community water supplies susceptible to drought; point-so-pollution prevention improving, non-point Sources Such as agriculture harmful; drought impacts navigation on the Mississippi; potential flooding due to rainfall with snowmelt or stalled frontal systems.

Iowa--Municipal water supply generally sufficient even under drought conditions; agricultural and livestock production would suffer significant losses in any drought; water-quality problems caused by agrochemicals leached into ground and surface water; many naturally tainted aquifers; potential flooding due to rapid spring snowmelt or convective storms.

Michigan-Abundance of water reaources; industry is major user; competition between upstream and downstream users; potential drought impacts on water level in Great Lakes and diversion practices; control of toxics in surface and groundwater and Great Lakes water quality has become prioriy, flooding infrequent, but usually due to rainfall during snowmelt.

Minnesota-Abundant water resources; drought affects Mississippi River management for water supply and navigation; Minneapolis-St. Paul needs alternative veto Mississippi for water supply; rural withdrawals depend on groundwater; potential flooding due to convective storms and snowmelt with rain in the spring.

Missouri-Abundant water resources; northwestern water supplies subject to drought stress; increased groundwater withdrawals and impact on water-baaed recreation during drought saltwater intrusion into aquifers; Occasional flooding due to Thunderstorms and stalled frontal systems.

Wisconsin--Water-rich state; industry is largest user; agriculture and tourism affected by drought 5 percent of State energy from hydropower, increasing competition for use; potential flooding caused by frontal systems, snowmelt, and convective storms.

Plains States Region

Drought is a frequent problem in this region. Competing uses of Missouri reservoirs--agricultural, tribal, recreational, and downstream--have led to management stresses. Small-community water supplies are vulnerable, water tables are low due to intense agricultural and urban consumption and groundwater depletion. Agricultural runoff has caused pollution, and the salinity of surface water is high.

Kansas--Water resources distributed unevenly, surface water in the east and groundwater in the west; most diversions are for irrigation; groundwater overdraft (e.g., the Ogallala Aq uifer) is occurring, and many areas are closed to further appropriation; adverse water-quality

impacts due to irrigation, petroleum production, agrochemicals, waste sites; agricultural droughts fairly routine; potential flooding due to stalled frontal systems, intense convective and tropical storms.

Nebraska-Abundant water supply although quantity varies anally, seasonally, and annually; irrigation is major user, localized groundwater overdraft; salinity problems in the South Platte River and canal systems originating in Colorado; interstate legal compacts and decrees on North and South Platte, Republican, and Blue Rivers; reservoir releases necessary to navigation on the Missouri; significant drought impact on agriculture, small community supplies, older well systems, and fish and wildlife; potential flooding due to thunderstorms, ice jams, and snowmelt in the RockyMountains.

North Dakota--Water is an important but scarce resource; reservoir system is critical due to seasonality of flows; limited water-distribution systems from reservoirs; agriculture, tourism, and recreation affected by drought high salinity of surface water agricultural drainage of wetlands; potential flooding due to spring snowmelt with rainfall.

South Dakota-Missouri River is the only reliable stream flow because of seasonal variability; demands on reservoir system from recreation, downstream navigation, agriculture, and future users--strong desire to stabilize agricultural production with reservoir system; drought disastrous for agriculture industry; eastern half of State vulnerable to groundwater overdraft interstate water resource conflicts on the Missouri; potential flooding due to snowmelt with rainfall, frontal systems.

Southwest Region

The agricultural economy here is vulnerable to drought.

Oklahoma-substantial water resources, unevenly distributed; groundwater in the west, surface water and reservoir storage in the east drought detrimental to agriculture, industrial-municipal water supply, tourism and recreation, instream flows, and hydropower, salinity problems in the Arkansas and Red Rivers; water-rights-allocation controversy; potential flooding due to convective and tropical storms.

New Mexico--Water scarce in generally arid state; surface water is completely appropriated and any supply reduction brings shortages; agriculture vulnerable to drought extensive storage capacity on perennial streams; groundwater overdraft in aquifers not associated with streams; irrigation is the largest user of water, quality **degraded** by municipal-industrial discharge into Rio Grande, saline and contaminated agricultural runoff, urban conlamination of some groundwater, most water use governed by interstate compacts, Supreme Court decrees, international treaty; intrastate conflict over instream-offstream uses; potential flooding due to local thunderstorms, melting snowpack with rainfall frontal systems from Pacific.

Texas-A semiarid to arid state; only eastern third of State has sufficient water on dependable basis; Houston, Corpus Christi, Dallas, and Fort Worth dependent on surface reservoirs of limited capacity Ogallala Aquifer of High Plains very slow recharge, substantial overdraft, Seymour Aquifer contaminated by oil-drilling activities; saltwater intrusion possible in coastal aquifers, salinity problems in Ogallala Aquifer and Rio Grande; low and hypersaline flows into coastaI estuaries and wetlands threaten species; agriculture and livestock losses due to drought; increasing competition between irrigation, urban uses, recreation, wildlife, tourism, and saltwater-intrusion correction; potential flash floods due to convective storms and **regional flooding** due to tropical storms and hurricanes; potential conflict with Mexico over allocation of groundwater.

Rocky Mountain Region

In this region, competition between instream and offstream users is growing, and water rights are controversial--American Indians vs. States vs. Federal Government. The salinity of surface and groundwater is high, agriculture in the region is vulnerable to drought, and *there are shortages in municipal water supplies during low flow.*

Colorado-Rapidly approaching maximum utilization of water resources; increasing conflicts among urban, agricultural, recreational and environmental uses of water, especially during drought; downstream States claim rights to water originating in Colorado; groundwater overdraft problems in arid eastern Colorado; conlamination of ground and surface water near toxic-waste sites; salinity problems in lower Arkansas River and in the San Luis and Grand Valleys; potential flooding due to thunderstorms, snowmelt, rain on saturated ground.

Monta na-Abundant water in major rivers; seasonal flow in smaller eastern rivers, so supply can be a problem; persistent water shortage in some areas; competition between irrigators and instream users (especially trout fishers); competition with downstream states; dependence on surface water makes agriculture more vulnerable; potential quality degradation due to mining, agriculture, forest practices; potential flooding due to snowmelt with rainfall, spring runoff.

Utah--Relatively scarce water resources; supply sources near population writers exhausted; variability of supplies (6 years of drought preceded by 4 wettest years on record); water-quality problems with seasonal low flows; localized drought at least once a year affects small communities, agriculture (especially grazing), instream flow for fish and wildlife; salinity high in lower reaches of streams; potential flooding due to rapid snowmelt with rainfall, intense thunderstorms, and lake rise.

Wyoming--Water resources dispersed unevenly, perennial streams in the west and ephemeral streams in the east; extended drought well-known affects agriculture and forest-fire hazard; most surface water committed under interstate compacts and court decrees; competition for surface waters between agriculture, municipalities, and industry; thunderstorms, snowmelt with rainfall, and stalled frontal systems can cause flooding.

Lower Colorado River Basin South Pacific Coast Region

The competition between municipal supply and irrigation in this region is increasing, as are conflicts between instream and offstream uses and over Indian, State, and Federal water rights. Salinity problems occur with surface and groundwater.

Arizona-Water a limited resource; shortages on Colorado River system (water apportioned to Arizona by the Colorado River Compact); groundwater overdraft due to both agricultural and population growth; industrial wastes, agrochemicals, salinity, and mining contamination of groundwater, 30 Superfund sites; Colorado River desalinization at national border, drought impact on rangeland, agriculture, recreational use of reservoirs; potential flooding due to snowmelt with rainfall, thunderstorms.

California-Most water in the north, most use in the south; entire State susceptible to drought (central and southern especially), which affects every use, from irrigation to municipal-industrial supply; population pressures in south and central; drought exacerbates groundwater overdraft, increases forest-fire potential, harmful to recreation and tourism; significant hydroelectric-power generation groundwater supply pressured by toxic contamination and coastal saltwater intrusion salinity problems in parts of San Joaquin Valley due to irrigration saltwater intrusion of Sacrament@ San Joaquin Delta interstate agreements and water-law constraints; growing competition between instream and offstream uses; potential flooding due to frontal systems from Alaska meeting moist tropical air.

Nevada-A very arid state; municipal water supplies insufficient in some cities, such as Las Vegas, Reno-Sparks, Lovelock, Wendover, Dayton, and Incline Village; agricultural demand relies on surface water, so is susceptible to drought competition among urban agricultural, municipal, tribal, and environmental uses; Colorado River withdrawals governed by Colorado River Compact and Nevada has inadequate share; bi-state agreements on three western rivers; widespread groundwater overdraft due to municipal and agricultural use; localized aquifer contamination; salinity high in Virgin River; wetlands and fisheries susceptible to drought; low flows create water-quality problems; endangered fish in some Great Basin lakes; potential flooding due to snow-melt and rain, localized thunderstorms.

Northwest and Pacific Region

In this region, municipal supplies for smaller communities are susceptible to drought, and competition among power-generation, fish and recreation, and instream and offstream uses generally is intense. Drought has had significant impacts on forest health.

Alaska-Water abundant overall; local supplies not sufficient for Anchorage and Juneau; sources not dependable during the winter when streams freeze or stop flowing, but drought not a major concern; suspended sediments in glacially fed rivers; ground and surface water pollution in populated areas; ice-jam floods common, intense storms and snowmelt occasionally bring floods.

Hawaii--Abundant water for size; small communities have only short-term water supply, but most droughts are short-term events; population and economic stress on island of Oahu leads to pollution; drought affects agriculture; major storms or hurricanes can bring flooding.

Idaho--Seasonality of surface water is major constraint on use, reservoirs supplement low flows; smaller communities have supply problems during drought; competition between municipal-industrial withdrawals and irrigation; drought affects agriculture, hydropower, tourism, recreation, forest-fire hazard; local pollution due to irrigation return flow, mine tailings, municipal-industrial waste; potential flooding due to snowmelt with rain, thunderstorms, ice jams.

Oregon-Abundant water in the west, limited water in the east; reservoir storage augments summer low flows, allows enormous hydroelectric production; coastal communities lack storage to deal with drought drought impacts on power production, fish, recreation agriculture, and forest-fire hazard; water-quality degradation from pasture and agricultural runoff, municipal and industrial discharge; groundwater overdraft in the east exacerbated by drought potential flooding due to snowmelt and rain in the west, convective storms in the east.

Washington--Water supply adequate, but unevenly distributed areally and seasonally; heavily populated areas of western Washington reaching limits of municipal-industrial supply; drought affects agriculture, hydropower (Washington produces 30 percent of U.S. hydroelectricity), tourism and recreation fisheries, wetlands, and navigation 60 percent of annual river flow through hydrological system is snowmelt; saltwater intrusion in San Juan and Island Counties, potential for all coastal areas; localized groundwater contamination potential flooding due to snowmelt with rain, thunderstorms in the east.

SOURCES: U.S. Geological *Survey (USGS), National Water Summary, 1985--Hydrologic Events and Surface Water Resources,* Water-Supply Paper 2300 (Washington, DC: U.S. Government Printing Office, 1986); USGS, National Water Summary *1986-Hydrologic Events and Groundwater Quality,* Water-Supply Paper 2325 (Washington, DC: U.S. Government Printing Office, 1988); USGS, *National Water Summary 1987-Hydrologic Events and Water Supply and Use,* Water-Supply Paper 2350 (Washington, DC: U.S. Government Printing Office, 1990); USGS, *National Water Summary 1988 -89--Hydrologic Events and F1oods and Droughts,* Water-Supply Paper 2375 (Washington, DC: U.S. Government Printing Office, 1991); U.S. Army Corps of Engineers, *The National Study of Water Management During Drought: Report of the First Year of Study (Fort Belvoir,* VA: U.S. Army, Institute for Water Resources, 1991); National Regulatory Research Institute, *Compendium on Water Supply, Drought, and Conservation, NRRI 89-15* (Columbus, OH: National Regulatory Research Institute, October 1989); letters from State water resource agencies.

Agriculture 6

Status

- **Adaptable private sector in a very competitive and growing world market.**
- **High payoffs to public investment--but declining public interest.**
- **Increasing environmental restrictions.**

Climate Change Problem

- **Potential changes in crop and livestock productivity.**
- **Market-driven responses may alter regional distribution and intensity of farming.**

What Is Most Vulnerable?

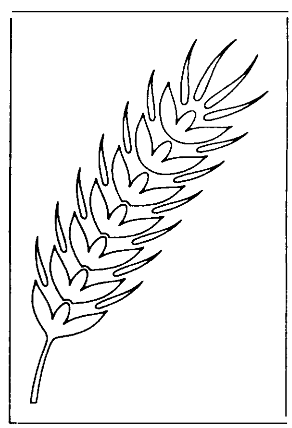
- **The long-term productivity and competitiveness of U.S. agriculture are at risk.**
- **Consumers and farm communities face high costs if the process of adaptation is slowed.**

Impediments

- **Institutional** rigidities and disincentives (e.g., commodity programs, disaster assistance, water-marketing restrictions).
- Uncertainty makes it hard for farmers to respond effectively.
- Potential environmental restrictions and water shortages.
- Technical limits-availability of suitable crops and practices for new climate.
- **Declining Federal interest in agricultural research and extension**

Types of Responses

- Remove institutional impediments to adaptation (in commodity programs, disaster assistance, water-marketing restrictions).
- Improve knowledge and responsiveness of farmers to speed adaptation (informational support, knowledge transfer, process innovation).
- Support research to enhance productivity through improved crops and farming practice (either directed at a general expansion in productivity or targeted to specific constraints and risks).



NOTE: Parts of this chapter are drawn from a paper prepared by W.E. Easterling for the Office of Technology Assessment (27).

OVERVIEW

In contrast to many natural resource systems examined elsewhere in this report, agriculture is an intensively managed, market-based system. Worldwide agricultural systems have evolved and adapt continuously to wide geographic differences in climate and to the risks associated with normal climate variability. In the past, agriculture has also been able to adjust to changes in economic conditions-such as the rapid changes in energy prices and export markets over the past two decades. There can be little doubt that the American agricultural sector will make further adaptations in response to changing climate conditions, with market forces rewarding and encouraging the rapid spread of successful adaptation. Yet, the possibility of unavoidable warming and drying in the major agricultural regions of the United States (see ch. 2,) argues for examining the potential for coping with climate change and for considering what public action might be appropriately taken in anticipation of an uncertain climate change.

For some farmers, simple adjustments in farming practices or crop selection may transform potential yield losses into gains. But for others, available responses will not compensate for the effects of harsher climates and water scarcity. The current limits to adaptation are well-illustrated by the geographic limits of where crops can be grown now. Without adequate moisture, farming becomes economically impractical. Increases in the intensity of conflicts between agriculture and the natural environment may also limit the extent to which adaptation is possible. For example, if a warmer climate leads to the expansion of intensive farming north into the Great Lakes States, land drainage could threaten ponds and wetlands, and increased use of farm chemicals could add to water pollution. In the arid West, greater demands for irrigation water could aggravate existing conflicts over the use of scarce supplies. Environmental concerns, whether aggravated by climate change or not, appear likely to constrain future expansion of agricultural production. Thus, despite adaptation, the possibility that agricultural yields will be threatened, particularly if climate becomes warmer and drier, cannot be discounted.

In a world where population growth is steadily increasing the need for food, any threat to growth in agricultural productivity must be taken seriously. For American farmers, already facing increasingly competitive world markets, any decline in productivity relative to the rest of the world could mean lost markets. For consumers, a decline in farm productivity growth could mean rising food prices. Estimates of economic effects of climate change on the United States range from damages of $10 billion to benefits of $10 billion (4). If the United States is to have a margin of security against the uncertainties of climate change, continued support is essential for research that enhances agricultural productivity and expands future options for farmers (e.g., new crops and improved farming systems).

Given the scale of the agricultural economy, a series of even small missteps and delays in the process of adaptation could, in the aggregate, prove very costly. Limited information and institutional impediments seem likely to restrict the farmer's ability to respond efficiently to a changing climate. The capability of the agricultural sector to respond to climate change can be improved through efforts to speed the movement of research results and new technologies into farm practice. In a future in which farmers must be increasingly responsive to change, the removal of unnecessary institutional impediments to adaptation is essential. For example, the framework of U.S. farm-support and disaster-assistance programs-which in many cases limit the farmer's incentives to change crops or farming practices rapidly and efficiently-should be reconsidered.

Climate change is almost certain to create both winners and losers, despite agricultural adaptation. Consumers will bear much of the cost of any decline in agricultural yields through higher prices. Some farmers might benefit from higher commodity prices, despite generally declining yields. Even so, other farmers will suffer because of relatively severe local climate changes and because of the inability--caused by a variety of factors-to respond effectively to change. Adaptation might itself result in some undesirable social and environmental impacts, particularly if climate change leads to rapid shifts in the geographical range of crops or in the intensity of farming practice. If climate warms considerably, the range over which major U.S. crops are planted could shift hundreds of miles to the north. Rapid geographical shifts in the agricultural land base could disrupt rural communities and their associated infrastructures. With agriculture and the rural economy already changing rapidly, and with the added uncertainties of climate change, it is impossible to do more than speculate about what effects climate change might have on rural communities.

This chapter provides a brief overview of U.S. agriculture and of the major trends facing it, examines the role that climate plays in agricultural production, and considers whether or not U.S. agriculture can be maintained under a changing climate. The nature of adaptation possibilities and the constraints that may limit the ability of the farm sector to respond successfully to a changing climate are considered. Finally, a potential role for the Federal Government in sustaining or improving agriculture's ability to cope with the uncertainties of a changing climate is discussed.


UNITED NATIONS, BY M. TZOVARAS

Past plant-breeding efforts have been successful in increasing productivity of crops such as wheat. Efforts to develop varieties that are better able to withstand environmental stresses, such as pests and droughts, may reduce the use of agrochemical inputs that are needed partly to compensate for unfavorable environments.

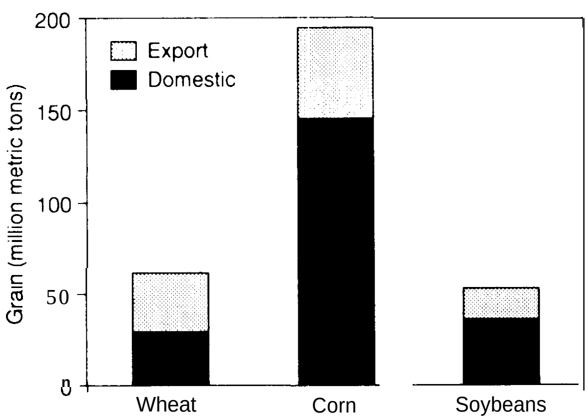
U.S. AGRICULTURE TODAY

The United States has an abundance of good agricultural land and a favorable climate for producing food, feed grains, and fiber. Cropland accounts for about 22 percent of the total U.S. land base (110). An additional 27 percent of the land base is in pasture and rangeland.[1] In 1990, the food sector[2] accounted for 17 percent of the civilian labor force, provided 15 percent of gross national product, and accounted for 11 percent of total U.S. exports (109). Although the relative importance of agriculture to the U.S. economy has declined steadily over time as the rest of the economy has grown in scale and complexity, agriculture remains of substantial economic importance.

[1] *Cropland* is land used for the production of cultivated crops (e.g., grains, hay, fruits, and vegetables) for harvest. *Pastureland is land used* for grazing, including once-forested land converted to forage cover and natural grasslands that are productive enough to support active management of forage plants. *Rangelands are natural* grasslands of low productivity.

[2] The food sector includes farm production plus the associated processing, manufacturing, transport, and marketing industries. The farm-production sector itself employs just 1.5 percent of the U.S. civilian labor force and provides 1.2 percent of the gross national product.

Figure 6-1—U.S. Production, Domestic Consumption, and Exports of Wheat, Corn, and Soybeans



NOTE: Three-year average based on 1989, 1990, and 1991 data. Exports and domestic consumption sum to U.S. production.

SOURCE: U.S. Department of Agriculture, Agricultural Statistics (Washington, DC: U.S. Government Printing Office, 1992).

The capacity of U.S. farmers to produce agricultural products far exceeds domestic needs. The United States produces more than half of the world's soybeans and 40 percent of the world's corn (maize). Much of the U.S. farm output is exported (fig. 6-l), and about 30 percent of the Nation's cropland is now producing for export (110). Even these statistics understate the current capacity to produce food. Of some 400 million acres (160 million hectares)[3] of cropland, about 65 million acres were withdrawn from production in 1991 (109) under various acreage-reduction programs, including the Conservation Reserve Program (CRP) (see box 6-A). Approximately 80 million acres now in pasture or forests could be converted to productive cropland if needed (112).4

The U.S. Department of Agriculture (USDA) divides the country into 10 regions for the

Box 6-A—Major Federal Programs Related to Agriculture and the Environment

Provisions of the 1985 and 1990 Farm Bills

- The Conservation Reserve Program (CRP) is designed to encourage farmers to voluntarily withdraw about 40 million acres (100 hectares)[1] of highly erodible or environmentally sensitive lands from crop production for a period of 10 to 15 years. In exchange, participating farmers receive annual rental payments ($50,000 maximum) and 50 percent cost-share assistance in establishing a soil-conserving vegetative cover on the retired land. Under the 1990 Farm Bill and new U.S. Department of Agriculture (USDA) rules for CRP operation, increased emphasis is placed on environmental benefits, including wildlife habitat and water quality improvements, as criteria for accepting land into the reserve program.
- The Wetlands Reserve Program (WRP) provides payment and cost-sharing assistance to farmers who agree to return previously farmed or converted wetlands to healthy wetland condition. WRP is intended to attract up to 1 million acres of wetlands by 1995, protecting these lands by easement for 30 years.
- Sodbuster and Conservation Compliance Provisions require that a farmer who converts highly erodible lands to crop production must have an approved conservation plan or forfeit eligibility for most USDA program benefits. The provisions apply to all highly erodible land that was not in production from 1981 to 1985. An estimated 224 million acres are subject to the Sodbuster requirements (25 percent of farmed land).
- Swampbuster provisions state that a farmer who converts wetlands, making possible the production of agricultural commodities, is ineligible for USDA program benefits (unless USDA determines that the conversion had a minimal effect).
- The Water Quality Incentives Program provides annual incentive payments of up to $3,500 per year for 3 to 5 years to farmers who implement a USDA-approved water-quality-protection plan. The voluntary program is

[1] To convert acres to hectares, multiply by 0.405.

[3] To convert acres to hectares, multiply by 0.405.

[4] This includes lands tbat have high or medium potential for conversion to agriculture (see table 7 in the appendix of ref. 112).

intended to result in the enrollment of 10 million acres. Limited appropriations have so far resulted in a smaller program than was initially authorized.

- The Environmental Easement Program provides annual payments and mst sharing for up to 10 years to farmers who agree either to have easements that provide long-term protection for environmentally sensitive lands or long-term reduction of water degradation. Participants must agree to a conservation plan to be developed in consultation with the Department of the Interior. Payment cannot exceed fair market value, No implementation has occurred to date.
- Pesticide Provisions require that producers (under threat of financial penalties) must now maintain records on the application of restricted-use pesticides for2 years. The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) (P.L. 100-532) was amended to make USDA responsible for programs on the use, storage, and disposal of agricultural chemicals.
- The Sustainable Agricultural Research and Education Program (SARE), also referred to as the Low-Input Sustainable-Agriculture Program (LISA), is a competitive grants program designed to respond to the need for a more cost-effective and environmentally benign agriculture, It is unique in blending research on farming systems with strategies for ensuring that findings are made usable to farmers, Emphasis is placed on farmer participation and on-farm demonstrations. The program is currently funded at $6,7 million, although funding of up to $40 million is authorized.

Continuing USDA Assistance Programs

- The Agricultural Conservation Program, initiated in 1936, provides financial assistance of up to $3,500 annually to farmers who implement approved soil- and water-conservation and pollution-abatement programs. An increasing emphasis is being placed on water quality projects.
- Conservation Technical Assistance, also initiated in 1936, provides technical assistance through the Soil Conservation Service to farmers for planning and implementing soil and water conservation and water quality practices.
- The Great Plains Conservation Program, initiated in 1957, provides technical and financial assistance in Great Plains States for conservation treatments that cover the entire farm operation. Assistance is limited to $35,000 per farmer. The program emphasizes reducing soil erosion caused by wind through the planting of windbreaks or the conversion of croplands to grass cover,
- The Resource Conservation and Development Program, initiated in 1962, assists multicounty areas in enhancing conservation, water quality, wildlife habitat, recreation, and rural development.
- The Water Bank Program, initiated in 1970, provides annual payments for reserving wetlands in important nesting, breeding, or feeding areas of migratory waterfowl,
- The Rural Clean Water Program, initiated in 1980, is an experimental program implemented in 21 project areas. It provides cost sharing and technical assistance to farmers who voluntarily implement approved best-management practices to improve water quality.
- The Farmers Home Administration (FmHA) Soil and Water Loan Program provides loans to farmers and farm associations for soil and water conservation, pollution abatement, and improving water systems that serve farms. FmHA may also acquire 50-year conservation easements as a means to help reduce outstanding farmer loans.

Research and Extension Activities

- The Agricultural Research Service conducts research on newandalternative crops and agricultural technology to reduce agriculture's adverse impacts on soil and water resources,
- The Cooperative State Research Service coordinates conservation and water quality research conducted by State Agricultural Experiment Stations and allocates funds for competitive grants, including those related to water quality research.
- The Soil Conservation Service (SCS) monitors the condition of agricultural soil and water resources, provides information to encourage better soil management, and supervises conservation-compliance plans.
- The Extension Service provides information and recommendations on soil conservation and water quality practices to farmers, in cooperation with State extension services and SCS.

(Continued on next page)

Box 6-A–Major Federal Programs Related to Agriculture and the Environment-(Continued)

Environmental Protection Agency Programs

- 1987 Water Quality Act Section 319 Programs (P.L. 95-217) require States and Territories to file assessment reports with the Environmental Protection Agency (EPA) to identify the navigable waters where water quality standards cannot be attained without reducing non-point-source pollution, including pollution from agricultural sources. States are also required to file management plans with EPA that identify steps that will be taken to reduce non-point-source pollution. All States have now filed assessment reports and management plans. The act authorizes up to $400 million for Implementing these plans, with $52 million awarded in 1992.
- The 1987 Water Quality Act National Estuary Program provides for the identification of nationally significant estuaries threatened by pollution, for the preparation of conservation and management plans, and for Federal grants to water-pollution-control agencies for the purposes of preparing plans. Under this program, USDA technical assistance to farmers has helped to reduce nitrogen and phosphorous discharges into the Chesapeake Bay by about 20,000 tons (1.8 million kilograms)[2] annually.
- The Federal Insecticide, Fungicide, and Rodenticide Act (P.L. 100-532) gives EPA responsibility for regulating pesticides, including agricultural insecticides and herbicides. EPA registers new pesticides and reviews existing pesticides to ensure that they do not present an unreasonable risk. The Agency may restrict or ban the use of pesticides determined to be a potential hazard to human health or the environment.
- The Safe Drinking Water Act (P.L. 93-523) requires EPA to publish drinking water standards for contaminants that can have adverse health effects in public water systems. These same standards are being used to assess contamination in groundwater supplies in private wells. The act also established a wellhead-protection program to protect sole-source aquifers from contamination by pesticides and agricultural chemicals.

2 To convert tons to kilograms, multiply by 907.

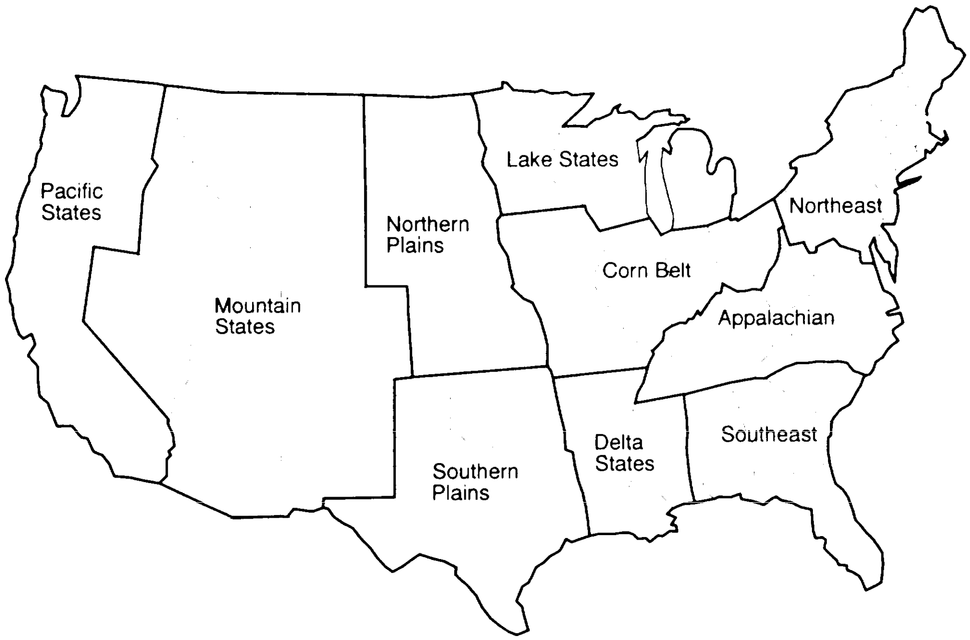
SOURCE: Office of Technology Assessment, 1993; U.S. Department of Agriculture (USDA), Economic Research Service (ERS), *Agricultural Resources: Cropland, Water, and Conservation Situation and Outlook*, ERS AR-27 (Washington, DC: USDA).

presentation of farm statistics, as illustrated in **figure 6-2.** About 65 percent of U.S. cropland is found in the Corn Belt region, the Northern Plains, the Lake States, and the Southern Plains (112). Of all the States, California, Iowa, Illinois, Minnesota, Texas, Nebraska, and Florida have the highest cash revenue from farming. Irrigation, rather than extensive farm acreage, accounts for the high value of farm production in several of these States (California, Texas, and Florida). The 17 Western States, Arkansas, Florida, and Louisiana account for 91 percent of irrigated acreage. California, Nebraska, Texas, Idaho, and Colorado account for almost half of the irrigated acreage. Overall, irrigation agriculture makes up only 5 percent of the land in farms and 15 percent of the harvested cropland, but provides a striking 38 percent of crop production, by dollar value (109). Much of this value is from fruits, vegetables, and specialty crops. Figure 6-3 illustrates the regional distribution of cropland and irrigated crop acreage in the United States.

Crop and Livestock Production in the United States

Agriculture varies considerably across the Nation due to differences in climate, geography, and economic conditions. Figure 6-4 shows several distinctive farming areas that differ significantly in farm size, income, and production (57). Although not exhaustive in covering the Nation's farm lands, this characterization of farms gives a fair sense of the diversity in U.S. agriculture. Farms of the Corn Belt and Great Plains provide the largest share of the Nation's grains and livestock products. Farms there tend to be large, and farmers rely on farming for most of their income. California produces fruits and vegetables, dairy products, livestock, and grains, with most crops coming from large, irrigated farms.

Figure 6-2-The USDA Agricultural Regions of the United States



SOURCE: U.S. Department of Agriculture, Soil Conservation Service, The Second *RCA Appraisal: Soil, Water, and Related Resources* on Nonfederal *Land* in the United *States-Analysis of Conditions* and *Trends,* Miscellaneous Publication No. 1482 (Washington, DC: U.S. Department of Agriculture, June 1989, slightly revised May 1990).

The Mississippi Delta region produces cotton, soybeans, and rice. Farms of the Coastal Plains produce mostly poultry, dairy products, cattle, and soybeans. The Wisconsin-Minnesota Dairy area provides dairy products, cattle, and corn, with most production coming from small farms. Tobacco, poultry, cattle, dairy, and soybeans are typical farm outputs of the Eastern Highlands and the Southeast Piedmont. Farms in these two areas tend to be small and often provide only a part of the farmer's total income.

The primary annual crops grown in the United States in terms of economic value and area of land use are the grain crops-corn, soybeans, and wheat (table 6-l). Although grown across the country, most of the output of these three crops comes from the Corn Belt, the Lake States, and the Great Plains. Box 6-B outlines how climate interacts with major U.S. grain crops. The cash value of fruits and vegetables (combined) is about equal to that of grains. Fruits and vegetables are largely grown under irrigation,[5] require a relatively small amount of land, and exist in such extensive variety that it is hard to imagine climate change threatening overall supplies-as long as water is available. However, individual growers of these crops maybe at some risk of losses under rapid climate change.

Trends in U.S. Agriculture

A general overview of major U.S. agricultural trends forms a baseline against which to measure the effects of climate change. Technical, social, and economic change have greatly transformed U.S. agriculture over the past 40 years. Regardless of climate change, U.S. agriculture faces several trends in the coming decades that will almost certainly persist.

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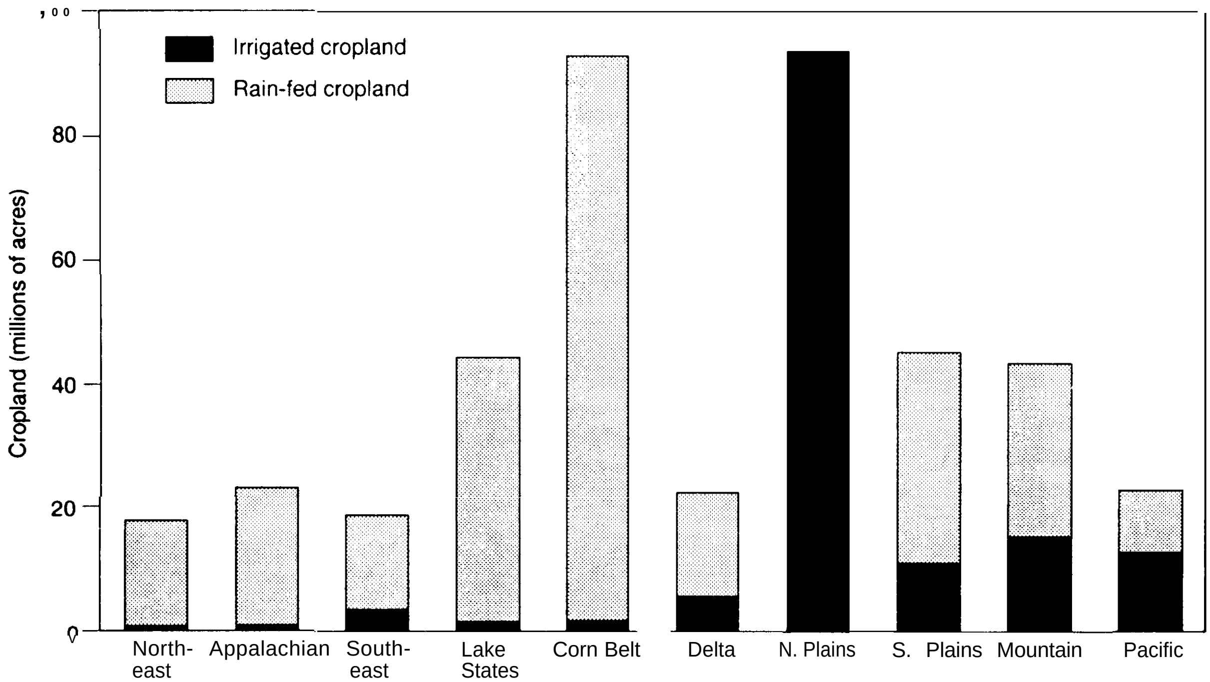
[5] About 65 percent of vegetable crops and 80 percent of orchard crops are irrigated (107),

Figure 6-3--Regional Distribution of Cropland and Irrigated Cropland in the United States



NOTE: To convert acres to hectares, multiply by 0.405.

SOURCE: U.S. Department of Agriculture, Soil *Conservation Service, The Second RCA Appraisal: Soil, Water,* and *Related Resources* on *Nonfederal/Land in the UnitedStates--Analysis of Conditions* and *Trends,* Miscellaneous Publication No. 14S2 (Washington, DO: U.S. Department of Agriculture, June 1989, slightly revised May 1990).

A center pivot irrigation system. The sprinkler system rotates to irrigate about 130 acres.

Slow Growth in Domestic Demand

Domestic demand for agricultural products will grow slowly, probably at no more than 1 percent per year (24). Population growth in the United States, the major determinant of domestic demand for agricultural products, is now at about 1 percent per year, and is expected to drop lower (114). Per capita income growth in the United States, even if it proves to be substantial, is unlikely to add much demand for agricultural products.[6]

Increasing *World Demand*

Worldwide growth in population and per capita income are such that world agricultural demand may increase by almost 2 percent a year over the next 50 years (20). Much of this new demand will

6 Between 1970 and 1992, the average consumer's food budget declined from 22 to 16 percent of total purchases (113). Only one-quarter of the consumer's food budget now pays for the cost of basic agricultural commodities, as compared with one-third in 1970 (113).

Figure 6-4-Characteristics of Nine Farming Regions

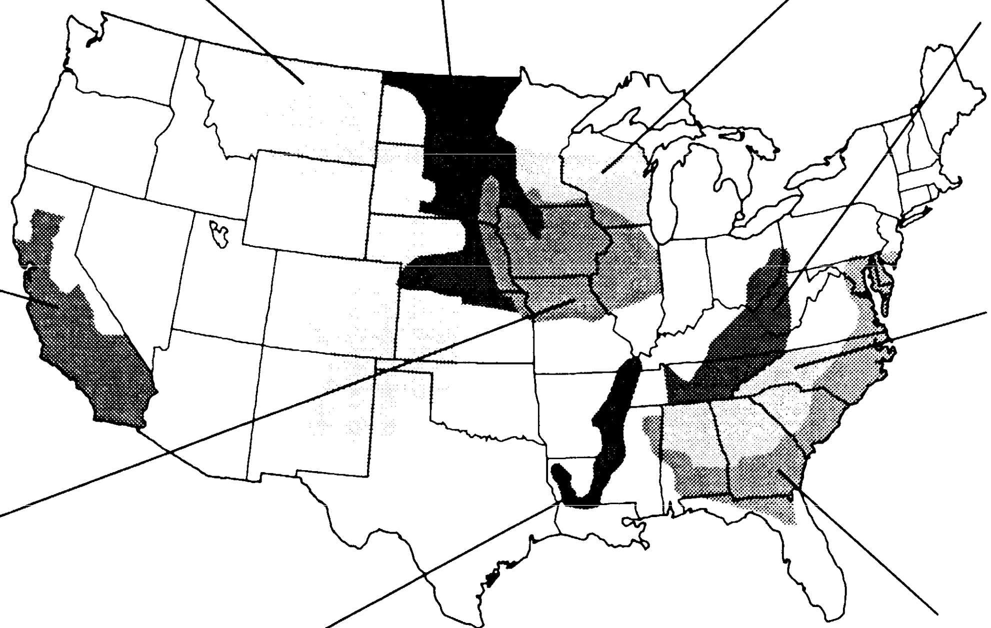
Western Great Plains. Typical farms have large acreages. The farm population relies more heavily on farming for income than in seven of the eight other regions. There are low rates of part-tlme farming and off-farm employment.

Western Corn Belt-Northern Plains. Most farmers here work full-time on their farms. The area relies on farming for income more so than any of the other region;. Farmers comprise the largest proportion of the total rural population (almost a third) in this region.

Wisconsin-Minnesota Dairy Area. This area relies heavily on dairy sales. A relatively low proportion of production comes from large farms. Fewer than 30 percent of farmers hold full-time jobs off the farm. The farm population is more dependent on farming income than in many other regions.

California Metro. Farm income is derived mostly from sales of fruits, vegetables, and other crops not covered by major Federal commodity programs. Average farm size is very large. The farm population is very mobile in comparison to other regions.

Eastern Highlands. This region is characterized by very low sales per farm, and a high percentage of sales coming from small farms. Farm operators are most likely here to work full-time off the farm, so farm households are not very dependent on farm Income.



Southeast Piedmont. This area relies less on farm program crops or dairy products than other areas. It has the h!ghest proportion of farmers with full-time off-farm jobs. Farming provides less than the average portion of total household income. Farmers make up only a small part of the rural population.

Core Corn Belt. Farm program crops provide most farm sales. Most farmers are full-time operators. The farm population (everyone who lives on a farm) earns more than half its income from nonfarm sources, but many rely mainly on farm income. Farm families make up much of the rural population.

Delta. This region is the most dependent on sales of farm program crops, which provide 85 percent of gross farm Income. Although less than 30 percent of farm operators work full-time off the farm, 54 percent have some employment outside agriculture, the national average.

Coastal Plains. Farms in this region rely somewhat more heavily on program crops and less on dairy sales than the national average. The percentage of farmers working full-time off-farm is about average, but the areas is less dependent on farm income than are most other regions.

SOURCE: Office of Technology Assessment, 1993, adapted from D. Martinez, "Wanted: Policies to Cope with Differences in Farming Regions," *Farmline,* vol. 8, No. 11, 1987, pp. 11-13.

Table 6-1--Harvested Acreage and Value of Principal Crops, 1991

	Acreage (millions of acres)	Crop value ($ billion)
Corn for grain	74	18
Hay	62	11
Soybean	58	11
Wheat	77	7
Cotton	12	5
Sorghum for galn	11	1
Vegetables	7	10
Fruits and nuts	4	8
Rice	3	1
Peanuts	2	1
Sugar beets and cane	2	2
Tobacco	1	3

SOURCE: U.S. Department of Agrfculture, Agricultural Statistics (Washington, DC: U.S. Government Printing Office, 1992).

come from developing countries. Meeting the growing need for food will require substantial gains in farm production throughout the world.

Increasing Productiviy and Output

U.S. agricultural productivity and yields are likely to continue to grow, but there is much disagreement over whether growth will remain as rapid as it has been in the past. Over the past four decades, U.S. farm yields increased at an annual rate of about 2 percent (24). Future gains in output are expected to be harder to achieve than they have been in the past (83), and gains averaging just 1 percent a year are predicted (1 12). For the United States, the best prospects for continuing to increase output lie in improved farm productivity. Conventional breeding strategies, more-efficient use of technical inputs, new biological technologies, and new information technologies may all contribute to improvements in farm productivity (103).

Competition for World Markets

With relatively stable domestic demands, U.S. farmers will increasingly look toward export markets. The best opportunity for growth in U.S. exports will be in the rapidly developing, populous countries of Asia and Latin America (24). However, uncertainty about future levels of agricultural production abroad leave it somewhat unclear whether foreign demand for U.S. agricultural products will increase. The advantage that U.S. farmers have long enjoyed in export markets could weaken as gains in productivity in foreign countries lower production costs relative to those in the United States.

Increasing Environmental Concerns

Strong environmental concerns could limit U.S. agricultural output and increase production costs.[7] A portion of the past gain in U.S. agricultural productivity has come at the expense of the environment. Salinization of soils, groundwater contamination, excessive erosion, and loss of wildlife habitat hav--in some areas-been the direct result of poor farm-management practices (112). Partially offsetting this has been the decline in land use for agriculture. As crop yields per acre increase, the total land area needed for U.S. agricultural production could decrease by as much as 30 percent over the next 40 years (112), thus reducing many land-use conflicts.

Society's increasing interest in protecting and preserving environmental values has led to stronger environmental policies. In the United States, this has meant taking some agricultural lands out of production (through the Conservation Reserve and Swampbuster Programs) and requiring changes in farming practices (Sodbuster Program). (Box 6-A describes Federal environmental programs related to agriculture; see also vol. 2, ch. 4, of this report.) The trend toward stronger environmental regulation will probably continue, with a likely increase in control overwater pollution from agricultural sources (e.g., fertilizers and pesticides). Stronger environmental protection policies may cause agricultural costs to rise, unless technologies that help farmers reduce environmental damage and land-use conflicts are developed.

[7] Although with other competing industrialized countries likely to be faced with similar environmental regulation it is somewhat unclear how Us. competitiveness might be affected.

Box 6-B–Primary US. Farm Products

Corn—Corn is the principal crop of the United States, grown on more farms than any other crop and with an annual production value of $18 billion in 1991 (table 6-l). Production is concentrated in the Corn Belt, which accounts for over half of U.S. corn acreage. Iowa, Illinois, Nebraska, Minnesota, Indiana, Wisconsin, Ohio, Michigan, South Dakota, and Missouri are the leading producer States, together accounting for over 80 percent of U.S. production. Corn yields are very susceptible to dry weather conditions, with drought-related losses often high. Water supply is most critical in the few weeks just before and after tasseling, which is when the tassel-like male flowers emerge. A dry spring t hat allows early planting can be important for maximum yields. Cool nights are also important for maximum corn yields; the warm night temperatures are a major reason the corn yields of the Southern Piedmont States are smaller than the Corn Belt's.[1] Reflecting the dependence on reliable moisture, farms that grow corn under irrigation have average yields almost 60 percent higher than do farms without irrigation in the same region. Irrigation is most common in the Western Great Plains States of Nebraska, Kansas, Colorado, and Texas. The United States exports over 20 percent of its corn and produces 40 percent of the world's supply. Most corn is used as livestock and poultry feed.

Soybeans—Soybeans are the second most valuable crop in the United States.[2] The primary soybean-producing region overlaps the Corn Belt. Illinois, Iowa, Minnesota, Indiana, Ohio, and Missouri are the leading producers. The soybean has a great ability to recover from climate stresses because of its indeterminate (continuous) flowering. The wide variety of genetic types available has allowed the crop to be grown in many climatic zones. Although grown in the South, soybeans do better in the cool-weather States. Yields in the South are hurt by uneven patterns of rainfall, diseases associated with dampness, and hot and dry conditions during the August pod-filling period. The United States exports 35 percent of its soybean production and provides over half of the world's supply. Soybeans are used in cooking oils, livestock feed, and several industrial applications.

Wheat—Wheat is the third-largest field crop in terms of total production value. Wheat is grown across the United States, although a large area of the Great Plains running from North Dakota and Montana down tothe Texas panhandle accounts fortwo-thirds of U.S. production. The Pacific States are also major producers. Kansas, North Dakota, Oklahoma, Washington, and Montana are generally the leading producers. Wheat infrequently grown in areas where there are few profitable alternatives. In dry areas, it is common to leave land fallow in alternate years to allow soil moisture to accumulate. Late spring freezes and inadequate moisture after flowering are the primary threats to yields. Winter wheat varieties are planted in the fall and harvested in spring or early summer-avoiding the threat of hot summer temperatures. These varieties account for about 75 percent of U.S. production. Where there is sufficient moisture and long growing seasons, winter wheat is sometimes double-cropped, with sorghum or soybeans grown during the summer. Spring wheats are planted in spring and harvested in late summer. These varieties are grown along the nort hem U.S. border, especially in Nort h Dakota, where winters are long and harsh. The United States produces about 10 percent of the world's wheat supply and exports half of its production.

Livestock and poultry—Livestock products (including poultry and dairy) account for about 53 percent of the total value of U.S. farm sales. Sales of cattle and dairy products are by far the largest component (almost 70 percent) of these livestock-related sales. The primary cattle regions are located west of the Mississippi and east of the Rocky Mountains, where t here is access to both grazing lands and feed grains. Much of t he U.S. production of earn and a large portion of soybean production goes to animal feed. Texas, Nebraska, and Kansas are leading cattle producers. Hog production is strongly linked to the corn-producing regions, with most production occurring in Iowa, Illinois, Minnesota, Nebraska, and Indiana. Poultry production is widespread, with much of it in the South.

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1 R.S. Loomis, Department of Agronomy, University of California at Davis, personal Communication, Apr. 22, 1993.

2 Excluding hay, which includes various grasses and legumes (such as alfalfa) grown for animal fodder.

SOURCE: Office of Technology Assessment, 1993; U.S. Department of Agriculture (USDA), Economic Research Service, *Agricultural Irrigation and Water Use*, Agricultural Information Bulletin 636 (Washington, DC: USDA).

Changing Farm Structure

The traditional small farm is gradually being replaced by the large, technologically sophisticated agribusiness.[8] Farms producing under $40,000 in annual revenues still account for almost 71 percent of the 2.2 million farms in the United States.[9] However, large farms-the 14 percent of farms with annual sales of over $100,000-now account for almost 80 percent of farm production (91). Small farming enterprises are increasingly less significant to the business of producing food.

Overall, farms are declining in number at 1 to 2 percent per year, with neighboring farm lands being consolidated into single, larger farms (91). As a result, average farm size has been increasing, rising from 213 acres in 1950 to 460 acres by 1990.[10] The trend toward consolidation of U.S. agricultural production into larger businesses will likely continue (24). Along with the increasing concentration of farm production on fewer large farms, there has been a decline in the rural population that depends on farming. on-farm populations declined from 15 percent of the U.S. population in 1950 to less than 2 percent in 1990. The declines in farm and rural populations are expected to continue (62, 101). By the time significant climate change might occur, farming will look much different from the way it looks today.

THE PROBLEM OF CLIMATE CHANGE

Climate and climate variability are already major risks to agricultural production. Agricultural losses due to climatic fluctuation are an expected part of farming. Farmers plant knowing that in some years, weather will cause poor yields. To minimize their exposure to climate risk, farmers take steps such as planting an appropriate crop, using water-conserving land-management practices, and diversifying sources of income. Such responsiveness suggests that farmers will adjust to perceived changes in climate variability, regardless of whether this is due to climate change or recognized as such by the farmer. However, future climate changes could present agriculture with unprecedented risks and circumstances.

Climate change, if it occurs, will be global, perhaps with large-scale winners and losers. There will be regional differences in the pace, direction, and extent of climate changes. Some regions are likely to be helped by climate change, while others are harmed. There is no way of knowing whether gains would offset the losses, but a changing climate would surely affect world agricultural markets and regional patterns of land use on a long-term basis. Not only will there be changes in average climatic conditions, but there may also be a change in the frequencies of rainfall and temperature-related extreme events. Although it is not clear that climate variability will increase, increases in mean temperature alone can lead to more-frequent periods of extended high temperatures (59). The changing frequency of extreme high-temperature events, rather than a gradual rise in average temperature, may present the greatest threat to farmers.

Adaptations made on the farm will be important in offsetting potential declines in yield. In some cases, simple adjustments in farming practices may transform potential yield losses into yield gains. Still, the extent to which adaptation will fully offset any negative effects of climate change might be constrained by cost and by limits to the availability of water and fertile soils. Conflicts over the environmental consequences of agriculture and the use of scarce water resources may become increasingly contentious (see ch. 5), limiting the possibilities for adapta-

[8] It is unclear how climate change might affect farm structure. The large, specialized farming enterprises may prove to be financially and managerially better prepared to respond to climate changes than the typical smaller farm. On the other hand, it could be that smaller farms with low capitalization, high diversification in source of income, and low input requirements will prove less vulnerable to climate change.

9 Farms producing under $40,000 in gross sales do not produce enough income to support a family by today's living standards. Many of these farms are owned by individuals who work full time in other jobs (91).

10 Farms producing over $100,000 in revenues average over 1,500 acres.

tion. Warming could eventually shift the potential range of crops hundreds of miles to the north (7). If crop ranges shift significantly and rapidly under a changing climate, communities that depend on agriculture could be greatly affected. Although most studies have concluded that there is no immediate threat to U.S. food supplies (4, 87), the possibility of even moderate reductions in long-terrn food supplies cannot be ignored as an underlying cause for public concern.

Sensitivity of Crops and Livestock to Climate Change

Virtually every aspect of farming is affected by weather and climate. If soils are too dry or too cold, seeds will not germinate. If soils are too wet, farmers have difficulty getting equipment into muddy fields to plant or harvest. Most importantly, climate controls biological productivity. In most plants, the process of flowering and developing harvestable organs depends in a complex way on the seasonal patterns of temperature and daylength. Crop yields are sensitive to daily and seasonal levels of solar radiation, maximum and minimum temperatures, precipitation, and carbon dioxide ($C0_2$), and to the soil-drying effects of winds and high temperatures. All of these factors could be altered under climate change. Whenever climatic conditions depart from those expected, they pose some risk to agriculture.

For agricultural crops, beneficial effects from increasing concentrations of atmospheric CO_2 are expected. Crops respond to increased concentrations of atmospheric CO_2 with greater photosynthetic efficiency, improved water-use efficiency, and greater tolerance for heat, moisture, and salinity stresses (1, 49, 52). The greater photosynthetic and water-use efficiencies result in larger and more-vigorous plants and increased yields (78).[11] It is not known precisely how the direct effects of higher $C0_2$ concentrations will influence crop yields under actual field conditions. Experimental results suggest that under a doubling of atmospheric CO^2 (and otherwise ideal conditions), yields may improve by 20 to 60 percent for crops such as wheat, soybeans, and rice--the C_3 crops (5, 49).[12] Yield increases of perhaps no more than 20 percent are expected for corn, sugar cane, and sorghum--the C_4 crops. The actual extent of the beneficial impacts from elevated CO_2 will depend on there being suitable temperatures and adequate supplies of nutrients and soil moisture.

Several factors may complicate the prediction that rising $C0_2$ will be a blessing for agriculture. The relative growth advantage of C_3 plants over the C^4 crops could change regional patterns of crop production. If C_3 weeds start growing faster, C_4 crops like corn and sugarcane could face increased competition from them. (The converse is also true, of course; C_3 plants could face reduced competition from C_4 weeds.) The nutritional quality of plants and grain might decline because of the changing balance of carbon and nitrogen (a result of increased uptake of carbon). This, in turn, might lead to increased insect damage, with insects consuming more plant material to compensate for lower nutritional quality (6).

Regional warming itself can be either beneficial or harmful. In more northern regions, where cool temperatures result in short growing seasons, the beneficial effects of increased seasonal warmth may dominate. Irrigated crops, which include most of the Nation's fruits and vegetables, should also benefit, especially if longer growing seasons allow double-cropping. Water, if available, can compensate for the stress of high temperatures. But warming tends to speed up the development of plants, shortening the period in which fruit formation and grain filling occurs, and

11 Note that despite improved water-use efficiency, crop water requirements may increase because of the larger plant size.

12 The categorization of plants as C_3 or C_4 is based on the mechanism by which CO_2 is used in the cell (see ch. 2). At elevated CO_2 concentrations, the inefficiency of the C_3 process in producing sugars is overcome, and C_3 plants respond with greater growth improvement than do C_4 plants.

so reduces yields. This effect on yields is especially notable in wheat and corn (2). Warmer nighttime temperatures, even in the absence of warmer daytime temperatures, will increase transpiration and can reduce a plant's ability to recover from the rigors of high daytime temperatures. High temperatures can damage the process of pollination (corn pollen begins to lose viability at 97 OF (36 'C)) and can damage fruit and flower formation (cotton fruit aborts after 6 hours at temperatures over 104 OF (40 'C)). High temperatures can stress plants directly, reducing growth rates in most crops at temperatures above 95 OF (35 'C). Finally, higher temperatures lead to increased evaporation, reducing water availability unless drying is offset by greater precipitation. Because water is generally the limiting factor in agricultural production, any soil drying tends to reduce yields. Corn yields are especially sensitive to moisture stress in the weeks around tasseling.[13]

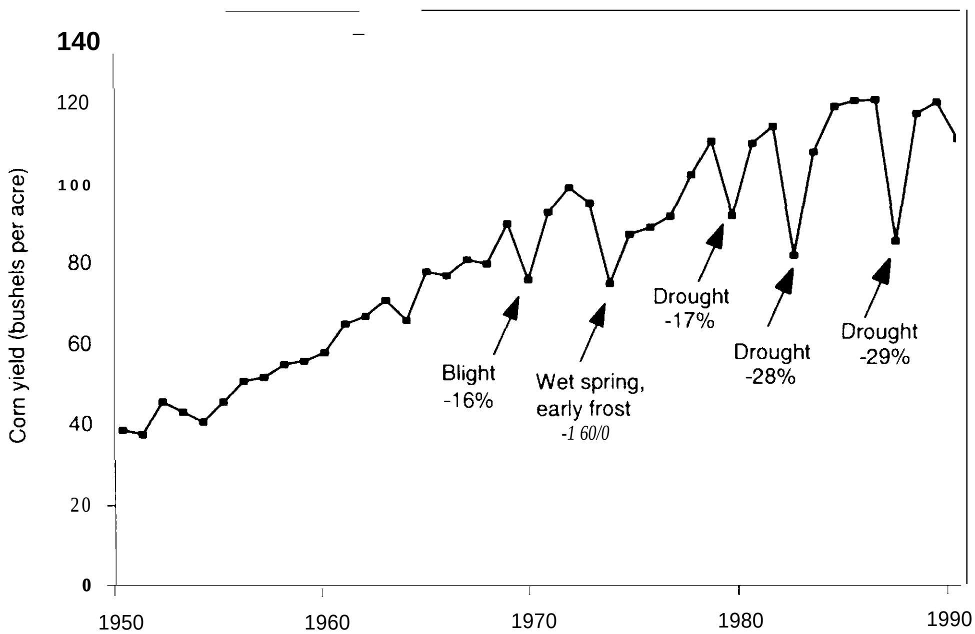
Crop yields and farm-management costs can be influenced in other, less-direct ways. Changes in the frequency or range of insects and fungal diseases seem likely to result from warmer climates, longer growing seasons, and changes in moisture levels. Pollination may be affected if the timing of plant development is out of phase with the presence of pollinating insects. Climate warming may alter the geographical distribution of existing pests now limited by winter temperatures and may allow for increased rates of successful invasion by exotic migrants. The severity of existing pest problems could be increased as longer growing seasons allow for the development of extra pest generations and as warmer temperatures raise the likelihood that pests will survive through the winter (70; see also ch. 2). Several pests, such as the southwestern corn borer and the corn earworm, could pose a greater threat to Corn Belt production. As a result, pest-management costs may rise. Farmers may also face changes in the costs of drying, storing, and transporting grain. A longer growing season might allow grains to be more fully dried in the fields, thus reducing costs. Grain-transport costs could be increased if reduced water flows limit barge traffic on the Mississippi River, as happened during the drought of 1988 (12) (see box 5-L). Livestock and poultry would also be affected by a warmer climate. Continued exposure of cattle to temperatures above 86 OF (30 'C) can slow weight gain, reduce milk production, and increase mortality (39, 50). Problems can be amplified if night temperatures rise disproportionately more than day temperatures (47) because animals need cool nights to recover from hot days. Livestock and poultry farming may also be affected indirectly, through changes in the price of feed, in water availability, in diseases, and in the availability and productivity of grazing lands. For example, any decline in acreage planted with crops in the Great Plains would lead to a corresponding increase in the land available for grazing. For the existing grazing lands, changes in soil moisture will have the greatest effect on the plant species composition and productivity (16).[14]

Climate change will threaten agriculture most in areas such as the western Great Plains, where heat stress and droughts are already problems and where increased irrigation would be costly. The extreme crop losses that occur during droughts provide a striking illustration of potential vulnerability. During the drought year of 1988, Illinois corn yields were almost 45 percent lower than previous years' (110). Figure 6-5 shows the sensitivity of U.S. corn yield to drought and other weather-related factors. Cropland now under irrigation in arid regions facing reduced water supplies and increased competition for water will

13 The male flowers that form on the top of corn plants are commonly referred to ss tassels.

14 Direct effects of elevated CO_2 may not be significant on grazing lands constrained by moisture and nitrogen. It is possible, however, that increased carbon uptake by forage plants without corresponding increases in the amount of nitrogen assimilated by those plants could reduce their nutritional value for livestock (40).

Figure 6-5-Corn Yields in the United States, 1950-91



NOTE: To convert bushels of corn per acre to metric tons per hectare, multiply by 0.063.

SOURCE: U.S. Department of Agriculture, *Agricultural* **Statistics** (Washington, DC: U.S. Government Printing Office, annual).

be at risk and will likely require increasingly sophisticated water-conserving technologies. In Western States, for example, warming could lead to a reduction or earlier melting of the winter snowpack that now provides much of the region's irrigation water (see ch. 5). On the other hand, if moisture levels increase and allow a northwest shift of the Corn Belt into the deep, fertile soils of the Dakotas, there might be little threat to yields. An expansion of the Corn Belt into that region is already under way (84). Over the past decade, plant breeders have developed corn varieties with a shorter growing season and thus have extended the corn region several hundred miles to the north.

The various effects of climate changes on agricultural yield are only suggestive of the potential economic harm from climate change. Exactly how consumer food prices and the profitability of agriculture are affected by climate change will depend on the aggregation of farm-level responses to changes in climate. Large-scale adjustments in the location and intensity of food production have the potential to offset much of the direct effect of climate change. Box 6-C describes some studies that have looked at the market responses and economic effects of climate change.

Conflicting Goals and Competing Demands for Water

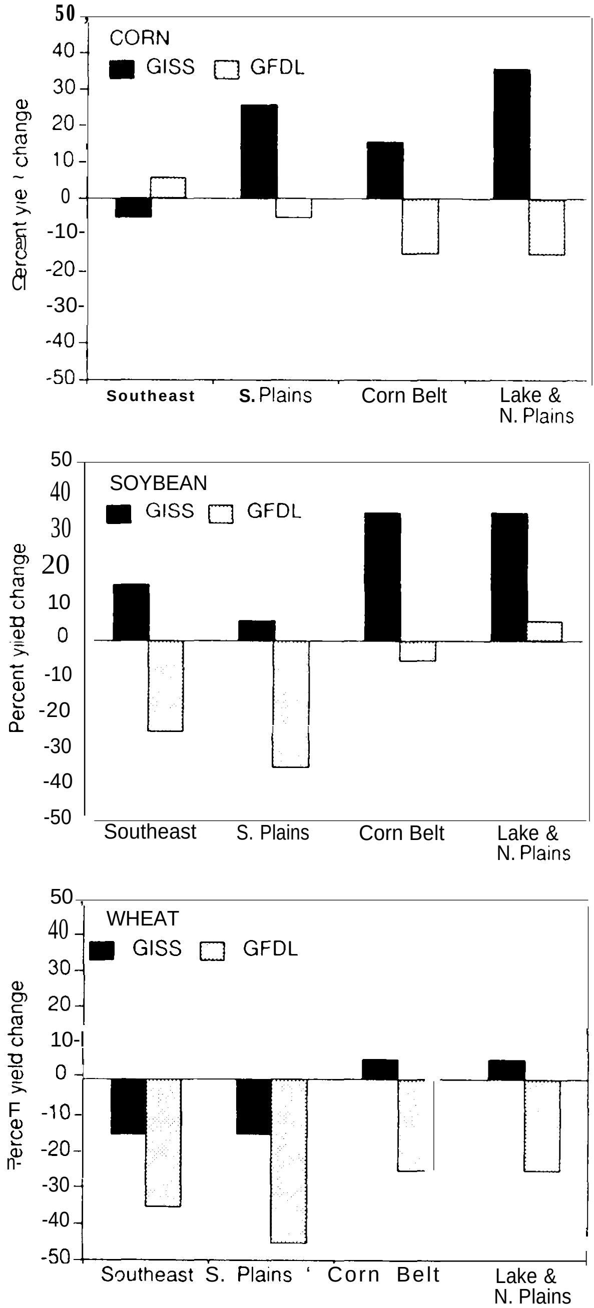
Agriculture's attempts to adjust to climate change could have several potentially undesirable consequences. The U.S. Environmental Protection Agency (EPA) warns that environmental concerns and constraints on the availability of land and water could add to the difficulty of maintaining agricultural yields under a climate change (87). Any increased use of irrigation water would be in conflict with the growing demand for other uses of water. The potential for a shift in the Corn Belt into northern areas of the Lake States raises particular concern. This is an area of thin soils, with poor drainage and uneven

Box 6-C—Previous Studies of Agriculture and Climate Change

In the 1980s, the Environmental Protection Agency (EPA) commissioned many major studies of the potential effects of climate change on U.S. agriculture (87)[1]. The Agency emphasized the use of crop simulation models to predict the effects of various climate-warming scenarios on crop yields (75, 80), and gave little attention to technical changes in agricultural systems or the adaptive responses of farmers. The warm ing scenarios were generated by general circulation model (GCM) experiments under the assumption of doubled atmospheric carbon dioxide (CO_2). The GCMs used predict eventual atmospheric temperature increases of 7 to 9 ‘F (4 to 5 ‘C) for many regions of the United States, and one of the models predicts severe drying for most of the agricultural land in the United States (see ch. 2). Representative projections of yield changes from two GCMs are presented in the figure at right.

EPA found that climate change would affect crop yields and livestock productivity and would result in a northward shift in the crop production zones. Although warming alone might lead to sharply reduced agricultural yields (over 50 percent decline in some regions), the direct effects of doubled CO_2 could offset much of the potential decline in crop yields. Still, EPA predicted that yields would decline substantially under the more-severe climate scenarios, especially where droughts become more frequent. Yields across the Southern and Central States were considered particularly vulnerable, largely because of drying. A few northern locations, such as Minnesota, were expected to show yield improvements

[1] The Council for Agricultural Science and T*nology(18) drew together perhaps the best overview of agriculture under climate change. Rosenberg and Crosson (79) investigated on-farm adaptation to climate change in the U.S. Midwest. A National Academy of Science study (65) reviewed the possible ways that agriculture could adapt to climate change.



SOURCE: C. Rosenzweig, “Potential Effects of Climate Change on Agricultural Production in the Great Plains: A Simulation Study,” in: *The Potential Effects of Global Climate Change on the United States,* Appendix C, Volume 1, J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental protection Agency, 19S9).

NOTE: Yields reflect CO_2 fertilization effect. GFDL=Geophysical Fluid Dynamics Laboratory; GISS=Goddard Institute for Space Studies.

(in some cases, by more than 40 percent). Including CO_2 effects and assuming no adaptive response, a reduction in the Nation's agricultural yields was projected as the most likely outcome of climate change.

Projected yield changes such as those described in the EPA studies suggest potential harmful effects of climate change but, ultimately, cost changes to consumers and agricultural producers are the concern. Exactly how consumer food prices and the profitability of farm production are affected will depend on farm-level reactions and market adjustments to climate change. Indeed, it is often not understood that farmers could benefit from the higher prices that would result from a reduction in all farm yields. Farming systems will change in response to crop productivity shifts and changes in commodity prices. Market-level adjustments in the location and intensity of food production worldwide will determine the prices faced by individual farmers and consumers.

Although the EPA studies did not explicitly consider farm-level adaptations, they suggested that farmers could act to offset some of the projected yield declines (3, 26,80). A few basic agronomic adjustments were considered (80). For dryland corn (i.e., corn that is not irrigated) in the Southern Plains, altered planting dates showed little effect in offsetting the yield reduction caused by climate warming. More dramatic effects of short-term adaptations were found for dryland and irrigated wheat. A switch in cultivars led to improved wheat yields in most of the simulations.

Others studies took a more comprehensive look at on-farm adaptation. One examined the natural resource base of the Missouri-Iowa-Nebraska-Kansas (MINK) region, investigating the effectiveness of several farm practices and innovations in offsetting effects of climate change (79), In the absence of adaptive response, they found that a permanent shift to warmer and drier climate conditions reduces net regional income by 1.3 percent. After accounting for direct CO_2 effects and short-term adaptations by farmers, regional economic losses are reduced to 0.3 percent(11). More significantly, the study considers plausible innovations in crop genetics and farm management that could further reduce the risks to the region's future economy t hat are posed by climate change.

Effects of economic adjustments through shifts in the location and intensity of production were considered in one study (3). Shifting crops to better-suited locations would be an important adaptive mechanism that would offset much of the potential economic cost of climate change. The study used a regional-market model of U.S. agriculture to examine the economic effects of changes in crop productivity due to climate change. Economic damages were significantly less than would have resulted in t he absence of shifts in the location and intensity of production. Economic effects range from damages of $10.3 billion to benefits of $10.9 billion, depending on which GCM scenario is considered (4). Depending on the climate scenario, overall crop production decreases by 20 percent or increases by 9 percent. Corresponding to these supply changes, commodity prices increase by 34 percent or decrease by 17 percent. In either case, farmers benefit while consumers bear the burden of higher prices under the harsher climate scenario.

One assessment of the world trade in agricultural products under climate change found that despite a potential for substantial effects of climate change on crops, interregional shifts in location and intensity of production and the opportunity for trade very much buffer the world from the threat of climate change (46). Price changes in international markets promote interregional adjustment in production and consumption. Essentiality no aggregate economic effect on the United States results, and economic effects on the overall world economy are estimated to be similarly small. Another assessment of world agricultural trade under a climate change found beneficial effects from world trade, with interregional adjustments offsetting 70 to 80 percent of the potential yield declines (81). Despite this finding, that assessment reached an important and less-than-optimistic conclusion: although the United States itself may not face market losses, some parts oft he developing world t hat must import food could suffer from higher food prices and an increased risk of hunger.

SOURCE: Office of Technology Assessment, 1993; W.E. Easterling, "Adapting United States Agriculture to Climate Change," contractor report prepared for the Office of Technology Assessment, January 1993.

terrain, raising the possibility of reduced productivity and increased environmental damage. Intensified farming in these northern lands would change the nature of an area now rich in forests, wetlands, and other natural habitats. Crop pests, if they expand in range or severity, might raise the Costs of main taining farm production. Increased use of chemical pesticides to counter these threats could add to water pollution problems. In areas where farming activity declines, there could be dislocations in local and regional economies (see box 6-D).

Box 6-D-Water Transfers in the West: Winners and Losers

Colorado provides a good illustration of the complexities surrounding already scarce water supplies in the West. Many climate models predict drying in the central parts of North America. With growing urban demands for water, increasing environmental concerns related to instream flows, and less water to go around, future conflicts over water seem likely to increase in intensit y. An examination of existing conflicts related to water transfers in Colorado illustrates some important social impacts that need to be considered when climate change policy is formulated.

Water transfers in Colorado are gradually moving water from irrigated agricultural to urban use. Over the past two decades, cities have purchased water rights on some 80,000 acres (24,300 hectares)[1] of agricultural land (out of some 3 million acres total irrigated land). The transfers are driven by economics. As costs for developing new municipal water supplies have increased, Colorado's cities have found it cheaper to purchase water rights from nearby agricultural areas. For farmers or ranchers, the sale of water rights has provided a desperately needed financial windfall at a time when the agricultural economy has been severely strained by high debt, poor weather, and low commodity prices. Faced with a sagging rural economy, the farmer who is offered by a city two to five times more than the value of water in agriculture sees a deal that is too good to refuse. For example, landowners in the Arkansas River Basin, who might lease a 40-acre field to a farmer for a profit of $2,500 per year, were able to sell the water rights to that land for $200,000 to the city of Aurora.

It would seem that such water transfers are a win-win situation. With farmers accounting for only 2 percent of the population and contributing 3 percent of economic output, yet consuming 92 percent of Colorado's water, small transfers of water from agriculture seem to offer the right solution to urban water shortages. The acre-foot of water that allows production of about $90 of wheat or $250 of beef will provide 4 years of water for a typical urban family of four. The farmer makes money by selling, and the city gets more than enough water to support a growing population. However, there are losers in almost every water transfer. The losers in Colorado have been the already poor counties and communities left with no future economic base after water sales to cities.

In the seven counties of the Arkansas River Basin in southeastern Colorado (see figure), large amounts of water have already been transferred to urban use. Prolonged droughts in the 1950s devastated the farm economy and triggered the first water sales to the city of Pueblo. In the 1970s and 1980s, there were major sales of water to the cities of Pueblo, Colorado Springs, and Aurora, spurred first by speculatively high water prices and later by economic troubles in the farm economy. By 1985, about 14 percent of the water rights in the seven-county basin had been sold for urban use. The dry climate of this area offers little opportunity for profitable farming unless land is irrigated. The decline in farm production has meant local suffering.

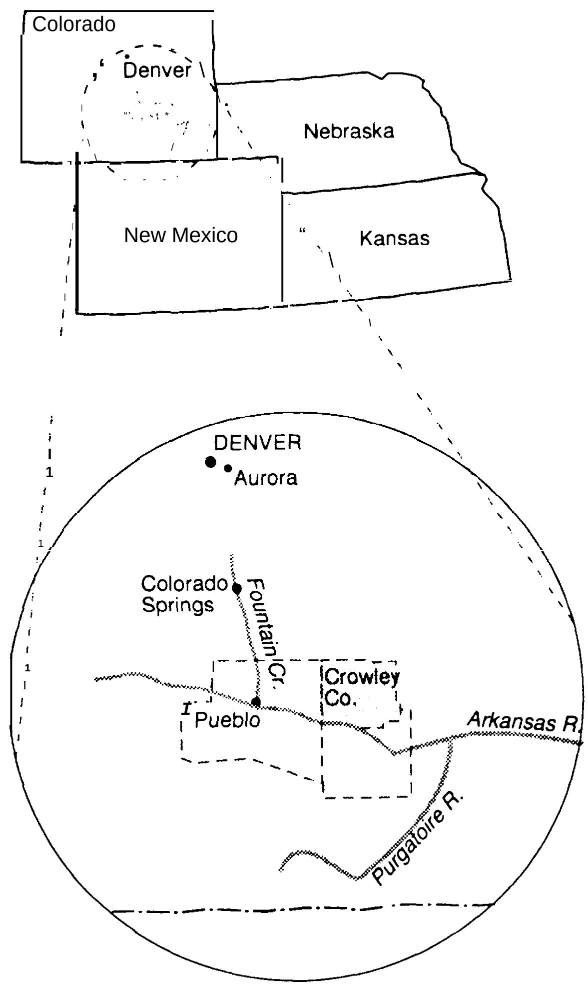
Particularity hard hit is Crowley County, which has seen 85 percent of its water rights transferred to cities. Little of the money received by farmers was reinvested in the local area. Rather, about 80 to 75 percent of the money went to pay taxes and debts of farmers who were already on the verge of bankruptcy. Crowley County already has the lowest assessed value of any Colorado county. Within the next few years, all land that has lost irrigation will be reassessed and the tax base will decline further. The burden of funding schools, local government, and other public services has shifted to the remaining few residents and farmers who chose not to sell their water. Colorado water law allows the transfer of water without regard to secondary consequences within the community. Despite attempts to jump-start the local economy with construction of a new prison, most prison employees have chosen not to live

[1] To convert acres to hectares, multiply by 0.405.

in the county, and many local businesses display "going-out-of-business" signs. Most of the farms that were once irrigated are now weed-covered and unsuitable even for grazing. The cities of Aurora and Colorado Springs have pledged to revegetate some fields with prairie grasses by providing temporary irrigation and seeding. It is not yet clear how intensively these lands can be grazed. Tens of thousands of other acres may remain weed-covered. Despite the rather bleak outlook, some residents are optimistic and look for opportunities to bring new business into the county.

Some workable solutions to conflicts over water between cities and farms are on the horizon. Ever since the Federal veto of the Two Forks Dam in 1990, Denver has been looking for new water supplies to support its growing population. Regional representatives have formed a plan outside "the traditional water development atmosphere." A combination of local utilities, cities, suburbs, farmers, environmental advocates, and the State have formulated a plan that may be appealing to all groups. Denver would purchase water from the South Platte River (currently used only by irrigators and off-limits to Denver), run the waste through an upgraded treatment plant, and then let the farmers use the cleaned-up wastewater for irrigation. This plan could make 50,000 to 100,000 acre-feet available to the City of Denver at much less than the cost of a new dam, although construction of an expensive water treatment facility would be required. Most interest groups are treating the plan as a serious alternative that minimizes losses on all sides. Other proposed solutions include the signing of "dry-year" option contracts between cities and farmers; in drought years, the city pays the farmer to forego planting crops and water is temporarily transferred to cities. These arrangements protect urban areas against drought shortages while maintaining long-term agricultural viability.

The Arkansas River Basin of Southeastern Colorado



SOURCE: Office of Technology Assessment, 1993.

Climate change could add to stresses on farmers across the western Plains. With the possibility of growing farm problems under a harsher future climate, more and more agricultural water is likely to be sold for urban use. In the past, extended droughts and poor financial returns have triggered abandonment of farming, the sale of water rights, and economic decline in rural communities. The prospect of climate change, raising the possibility that farming may have to be abandoned in large areas of the semiarid West, adds another layer of concern to these third-party effects.

SOURCES: Office of Technology Assessment, 1993; C.W. Howe, J.K. Lazo, and K.R. Weber, "The Economic Impacts of Agriculture-to-Urban Water Transfers on the Area of Origin: A Case Study of the Arkansas River Valley in Colorado," *American Journal of Agricultural Economics*, vol. 72, No. 5, December 1990, pp. 1200-1204; National Research Council, *Water Transfers in the West: Efficiency, Equity, and the Environment* (Washington, DC: National Academy Press, 1992); M. Obmascik and P. O'Driscoll, "Colorado Water: The New Harvest," *The Denver Post*, July 19-22, 1992.

So much land and water is used for agriculture that any climate-induced changes to agriculture would have profound effects on competing uses for these resources (see ch. 5 and vol. 2, chs. 4 and 6). Cropland and pasture account for 30 percent of land use, and irrigation of agricultural land accounts for 84 percent of consumed water (88). Land and water resources are particularly vulnerable to expansion of agricultural activity and to increases in the intensity of irrigation or in the use of farm chemicals. Many agricultural States have already lost much of their original wetland area (see vol. 2, box 4-E) and forest cover to agriculture.

Competition for scarce water is likely to be particularly important under climate change (3, 4). Whether increases in irrigation are possible will depend on water availability and costs. If withdrawal of water for agriculture does increase, wildlife habitat and other services that depend on freshwater flows will be increasingly threatened, particularly if climate change reduces or alters the seasonal timing of stream flows. On the other hand, without sufficient water for agriculture, farm yields will be reduced. The western regions, already facing water shortages, may see renewed pressures to construct large water-resource-development projects (see ch. 5). These projects have in the past been in conflict with the goal of protecting natural habitats.

Water quality may also be affected by a changing climate. Farm chemicals and wastes can infiltrate groundwater, and surface-water runoff and drainage can carry salts, farm chemicals, and sediments to adjacent water bodies (see box 6-E). With altered patterns of precipitation and regional agricultural activity and with altered dilution rates in streams and aquifers, the nature of the water pollution problem on a regional scale could change substantially. Concern over pollution

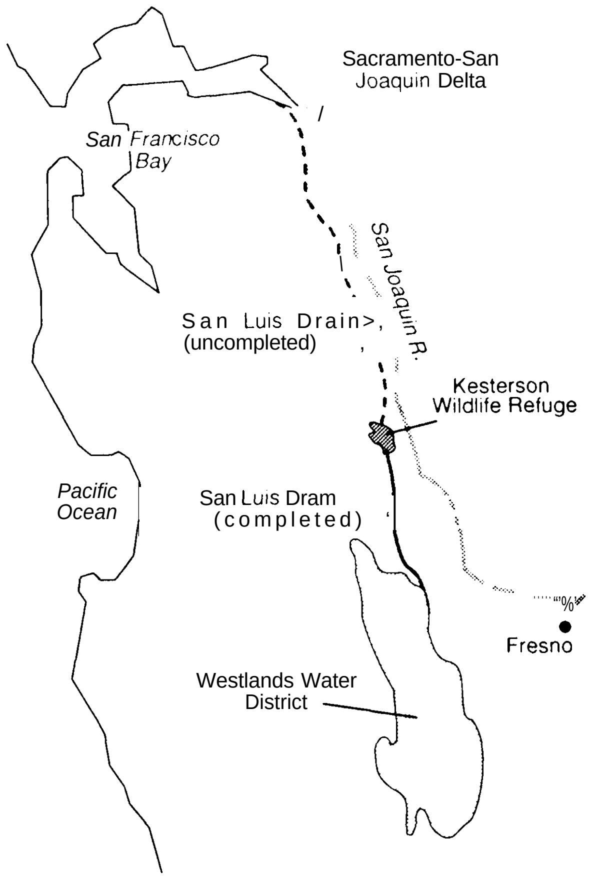
Box 6-E—irrigated Agriculture and Water Quality: The Kesterson Case

Climate change models suggest that many parts of the interior United States will become hotter and drier. One potential response to this is to increase the area of cultivated land under irrigation. Although increased irrigation may prove to be attractive to farmers, it is not without environmental costs-including potential damage to soils, water quality, and wildlife. The case of the Kesterson National wildlife Refuge shows how failure to anticipate potential waterquality problems can lead to severe contamination and suggests that future public efforts to support irrigation should proceed with caution and a thorough understanding of risks.

The Kesterson National Wildlife Refuge was established in 1970 along the San Joaquin River in California's intensively farmed Central Valley (figure). The 5,900-acre (2,390-hectare)[1] refuge harbored a diverse array of migratory and resident waterfowl, including ducks, geese, herons, and coots, as well as an assortment of fish, mammals, and raptors. Located in a State that is estimated to have lost more than 90 percent of its wetlands over the past two centuries, Kesterson appeared to be a crucial part of efforts to conserve California's biological heritage. In the spring of 1983, some of the ducks, coots, grebes, and stilts born at Kesterson Reservoir at the southeastern edge of the refuge emerged from their eggs deformed and crippled-with oddly shaped beaks, missing wings, twisted legs, and unformed skulls. Many died shortly after hatching. The U.S. Fish and Wildlife Service, which had investigated fish die-offs at Kesterson in 1982, conducted laboratory analysis that suggested that the disappearance of fish and the deformities of birds stemmed from a common cause—unusually high concentrations of selenium in the Kesterson Reservoir water. Trace amounts of selenium occur naturally in the soils of central California, as in many parts of the arid Southwest. The contamination of Kesterson Reservoir was caused by a combination of water development projects and irrigation practices. Selenium had leached from agricultural soils, moved through drainage systems, and became concentrated in the Kesterson Reservoir. At high concentrations, the selenium proved deadly. Kesterson Reservoir lies at the drainage end of the San Luis Unit of the Westlands Water District, operated by the Bureau of Reclamation as part of the huge Central Valley Project. The saline soils of large sections of the San Luis area were not easily used for irrigated agriculture. The success of irrigated agriculture in saline soils

[1] To convert acres to hectares, multiply by 0.405.

Kesterson Reservoir and Surrounding Areas



SOURCE: Office of Technology Assessment, 1993, adapted from R.W. Wahl, *Markets* for *Federal Water: Subsides, Property Rights,* and the *Bureau of Reclamation* (Washington, DC: Resources for the Future, 19s9).

depends on the application of enough water to flush salts out of the upper layers of soil. But the soils of San Luis presented an additional complication—they are underlain by an impenetrable layer of day that prevents the drainage of irrigation water. If the soils were irrigated enough to flush away salts, the poor drainage would cause the water table to rise, drowning roots of crop plants and depositing more salts in surface soils. Subsurface drainage was necessary to make the cropland productive.

As part of larger efforts to bring water to the Central Valley, the Bureau of Reclamation began planning water supply systems in the San Luis Unit starting in the 1950s, and by 1960, was authorized to begin construction of a system that came to include the San Luis Dam, Canal, and Reservoir. To achieve the proper balance of irrigation and drainage for agricultural production, the Bureau of Reclamation planned an extensive 188-mile (300 -kilometer)[2] drainage system to take drainage flows from the San Luis Unit into the Sacramento-San Joaquin Delta. Only the first 85 miles of the drain were ever completed. By 1975, the drain had reached Kesterson Reservoir—and that is where it stopped. Controversy over potential effects on water quality in the Delta and lack of Federal funds prevented completion of the full drainage system.

Since 1975, drainage water carrying selenium and other salts leached from the San Luis soils have emptied into the Kesterson Reservoir. Over the years, selenium and other potentially toxic trace elements concentrated in reservoir waters. The selenium was further concentrated in vegetation and small organisms on which waterfowl feed-a process known as *bioconcentration*—eventually producing the startling birth defects and mortality among young birds seen in 1983. Concern over possible risks to humans led the State to issue a health advisory, warning against eating duck hunted on the refuge. California's State Water Resources Control Board found concentrations of selenium up to 10 times higher than permitted by public health standards and other trace elements in amounts that exceeded Environmental Protection Agency (EPA) water-quality standards. By 1985, the Board declared the San Luis drainage water a hazardous waste that would have to be treated and cleaned up accordingly. Drainage into the reservoir was finally halted in 1986. [n less than a decade, Kesterson went from being a cornerstone of California's wildlife conservation program to a national symbol of environmental disaster. The Kesterson case is an extreme example of how irrigated agriculture may harm water quality-a particularly ill-fated confluence of Federal water projects, natural soil properties, and conflicting goals. However, the Kesterson problems are not unique. In the East, soluble salts have long ago been washed from

2 To convert miles to kilometers, multiply by 1.609.

(Continued on next page)

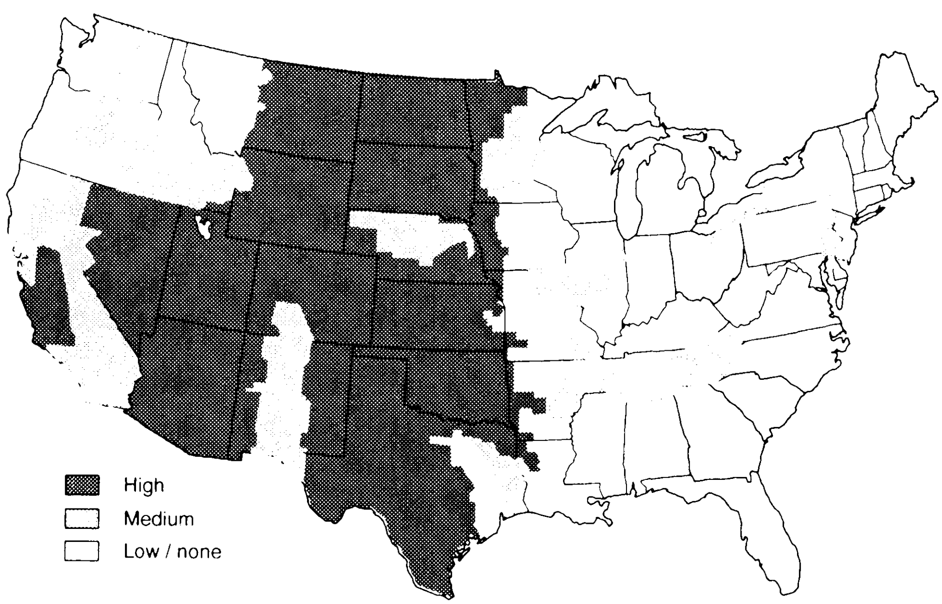
Box 6-E-irrigated Agriculture and Water Quality: The Kesterson Case-(Continued)

the soils by rainfall. But in the West, the accessibility of salt-bearing formations and iow rates of precipitation combine to make much of the region subject to salinity problems (figure below). Even on nonirrigated cropland, saline deposits can develop in areas of poor drainage. Dryland farming practices, alternating crop and fallow years (apossibleadaptation to climate change), maythemseivesaddto salinity problems. Crop-fallow rotations useless water than would natural vegetation, and the unused soil water can carry salts to low-lying areas.

Can a case like Kesterson happen again? Federal actions at water projects around the Nation will undoubtedly be more cautious in the future. However, in most Western States, irrigation and consumptive use still take priority, while protection of adequate water flows and water quality for wildlife, fish, recreation, and other natural uses receive short shrift (see ch. 5). Climate change may well increase the demand forwaterdiversions for irrigation, potentially leading to increased conflicts over water use and environmental quality.

SOURCES: Office of Technology Assessment, 1993; A. Dinar and D. Zilberman (eds.), *The Economics and Management of Water and Drainage in Agriculture* (Boston, MA: Kluwer Academic Publishers, 1991); R.W. Wahl, *Markets for Federal Water: Subsidies, Property Rights, and the Bureau of Reclamation* (Washington, DC: Resources for the Future, 19S9).

The Potential for Water-Salinit y Problems



SOURCE: U.S. Department of Agriculture, Soil ConservaticService, *The Second RCA Appraisal*, Miscellaneous publication No. 14S2, 19S9.

from agricultural sources may limit the extent to which agriculture can adjust to climate change.

Although an overall expansion in cropland seems unlikely (112), spatial shifts in the pattern of land use may still be disruptive to natural environments (4). For example, increases in farm acreage are projected in the environmentally sensitive lands of the Lake States and the erodible lands of the Northern Plains. As a result of climate change, economic forces could bring an additional 3 million acres into new production in the South, with much of this cropland created by the clearing of forests (23). Such an expansion of farming into highly erodible or environmentally sensitive lands would be inconsistent with environmental goals (see box 6-A).

TECHNOLOGIES FOR ADAPTATION TO CLIMATE CHANGE

Past experience suggests that U.S. farming is flexible and innovative enough to permit relatively quick changes in management practices and in crop choice. History is replete with examples that illustrate the responsiveness of agriculture and agricultural research to challenges (see boxes 6-F and 6-G). In responding to climate change, farmers can draw on the large array of tactics and strategies they already use to protect themselves against climate risk (see box 6-H). Many tactics, such as changing planting dates or cultivars, require little change in the nature of farm management and can be implemented rapidly. Other adjustments, such as adding irrigation or switching crops, require substantial changes in farm equipment and management, and will occur somewhat more gradually. Together, these may provide the first line of defense against climate change.


USDA, AGRICULTURAL RESEARCH SERVICE

An ARS soil scientist inspects severely salt-damaged farmland in California's San Joaquin Valley.

Agricultural adaptations that draw on current practices may be effective for a time in dealing with climate change. There is a reasonable chance, though, that climate change could eventually overwhelm the effectiveness of current adaptation possibilities. That is a compelling reason to consider the long-term prospects for new technologies. Long-term adaptation may require fundamental improvements in the technologies available to farmers. In the past, expansion of agricultural technology has occurred both as a market-induced response to a changing environment and through publicly supported efforts aimed at overcoming perceived resource constraints. U.S. farming has been supported in this by: 1) a sophisticated system of agribusiness; 2) a publicly supported land-grant university, research, and extension system that channels technology to farmers; 3) a transportation infrastructure organized to move food rapidly from the farm to an interlocking system of local, regional, national, and world markets; and 4) a market economy that quickly rewards successful adaptation. These institutions have provided U.S. agriculture with the ability to adapt to rapidly changing economic conditions and should, if well-maintained and directed, provide the basis for future adaptation to climate change.

Adaptation may be slowed by impediments to flexibility in crop choice, such as those imposed by Government farm-support programs (54). The net effect may be to discourage transition to cropping systems that are better suited to the changed climate. Uncertainty and inadequacies in the information available to farmers, both about climate change and effective responses to it, could slow the rate of adaptation. Policies that restrict or distort agricultural markets are also important constraints to effective adaptation (18, 20). The subsidies provided to farmers in some countries tend to discourage farming in regions where agriculture is more productive, and so raise overall costs of world food production.

Box 6-F—Historical Examples of Adaptability in Agriculture

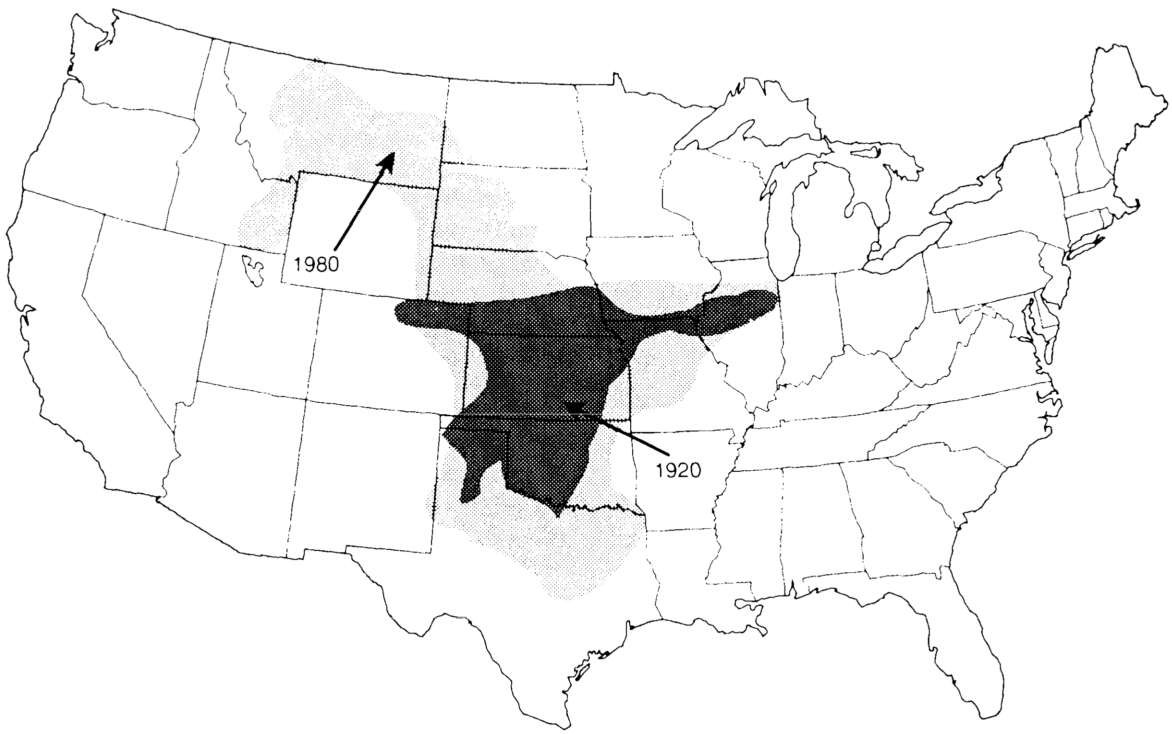
Adaptation of crops to different climatic regimes: the case of wheat and **corn**

Expansion of a crop into anew region often requires that the crop be adapted to a new climatic regime. Here we describe how hard red winter wheat and dryland corn have undergone such adaptation.

Hard red winter wheat—Hard red winter wheat has accounted for about half of all wheat produced in the United States. The figure below shows how much the production zone for hard red winter wheat expanded from 1920 to 1980 (76). Once limited primarily to Nebraska and Kansas, the crop is now grown as far north as the Canadian Prairie Provinces and as far south as the Rio Grande River. This process of expansion has occurred even during times of hardship in the farm economy (such as the prolonged drought and economic depression in the 1930s and the surplus production and depressed crop prices in recent years).

Through the efforts of crop breeders and agronomists, hard red winter wheat has been effectively adapted to colder temperatures and drier conditions. The crop is now grown in northern locations that are about 6 °F (3.5 °C) cooler and 15 percent drier than where growth was possible in 1920. The southward expansion of the crop has not been as striking as the northward spread. Still, average annual temperatures at the current southern boundary of the crop are almost 3.5 ‘F (2 ‘C) higher than they are at any location in the crop zone of 1920. The expansion in the hard red winter wheat range has come about from steady improvements in productivity made possible by the development of improved wheat varieties and farm-management practices (42).

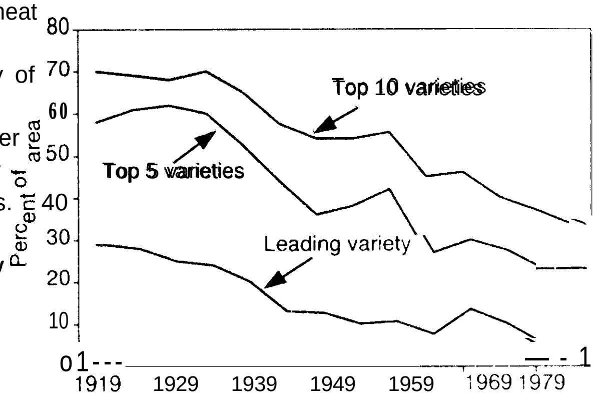
Extent of the Hard Red Winter Wheat Zone in 1920 and 1980



SOURCE: N.J. Rosenberg, "The Increasing CO_2 Concentration in the Atmosphere and Its Implication on Agricultural Productivity, Part II: Effects Through CO_2-induced Climatic Change," *Climatic Change, vol.* 4, 1982, pp. 239-254.

The development and adoption of semi-dwarf varieties in the 1940s (varieties whose stalks support heavier, grain-laden heads) boosted wheat productivity (21). Continued breeding efforts since the 1940s have resulted in the great diversity of wheat varieties now being used by US. farmers. The progression to greater varietal diversity over time (see figure) has been associated with better adaptation] of wheat to local growing conditions. Breeding for disease resistance helped the expansion to the south. Selective breeding for cold-hardy varieties of hard red winter wheat helped the expansion of wheat to the north.

Proportion of Wheat Planted to Leading Varieties in the United States



SOURCE: D.G. Dalrymple, "Changes in Wheat Varieties and Yields in the United States, 1919-1984," *Agricultural History, vol. 62, 1988,* pp. 20-36.

Improved farming practices, especially the use of nitrogen fertilizers, better soil-moisture management practices, and large self-propelled machinery, have increased the productivity of wheat growers. The practices of stubbling-in (i.e., direct seeding of winter wheat into untilled fields immediately after harvest of the previous crop) and snow trapping (e.g., using snow fences to collect snow on fields) have reduced the risk of winterkill and permitted an expansion of the crop northeastward into Canada's western agricultural Provinces (86).

The past performance of the research community in developing new ways for wheat to overcome climatic constraints suggests the enormous capacity of the community to respond in the future. For example, as a consequence of breeding programs, the genetic diversity of hard red winter wheat is increasing; this greater genetic diversity should provide the raw material for further progress in crop development (19). This is but one example of the promise for future progress in adaptive agricultural research.

Dryland corn—Perhaps even more remarkable t han the spread of hard red winter wheat into the Canadian Prairie Provinces is the recent adaptation of dryland corn to that same region. Farming systems in the semiarid northern Great Plains have historically suffered from overdependence on a narrow range of crops, especially wheat (56). This overdependence made the region vulnerable during times when wheat prices were depressed. Recognition of this problem caused farmers, working in concert with the local agricultural research establishment, to seek an alternative crop.

The Lethbridge Research Station devoted 8 years of research to adapting corn to the climate of southern Alberta (56). Relative to regions of t he United States that produce significant quantities of dryland corn, southern Alberta is drier, the frost-free season is shorter, cumulative seasonal warmth is lower, and day length (period of daylight) is longer. The long day length can delay flowering, and the short growing season then provides little time for maturation.

In response to these challenges, plant breeders at Lethbridge have developed hybrids that have reduced sensitivity to day length and a short juvenile phase, so that the tassel starts to grow within a week of plant emergence. Moreover, breeders have successfully selected for varieties with a short interval between the opening of the mrn tassels and the production of silk, which appears to give corn plants increased tolerance to drought. In dryland trials, corn yields from these new varieties are competitive with those of barley and wheat (56). These results clearly illustrate how directed research (i.e., the desire to diversify cropping systems in sout hem Alberta) can overcome major climatic constraints on crop production.

Box 6-F—Historical Examples of Adaptability in Agriculture—(Continued)

Rapid introduction of new crops: the case of soybeans

Climate change may necessitate widespread and relatively rapid shifts in the types of crops currently grown in the United States. How easily such a shift could be accomplished will depend on the available pool of crops that will flourish under the changing climate and on their production costs and markets. The expansion of soybeans into U.S. agricultural production, especially since World War II, is a vivid example of the rapidity with which the Nation's production systems can be modified to accommodate a new crop.

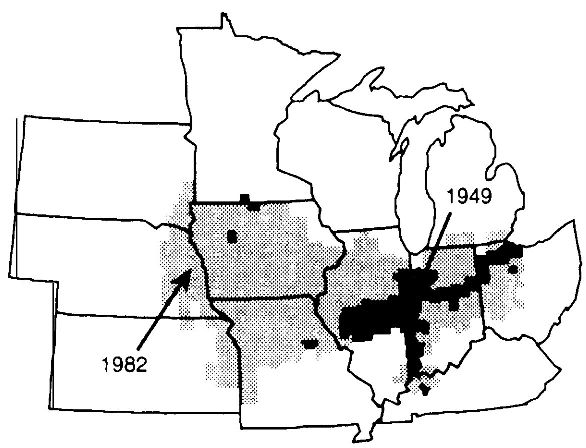
Soybeans have been cultivated in the United States since the early 1800s, although most were used for forage until the middle of this century (71). In 1920, there was no measurable acreage planted in soybeans in the Corn Belt States. Acreages planted in soybeans remained quite low until just before World War II (34). At that time, the United States imported over 40 percent of the soybeans that were used domestically.

During World War II, a growing demand for margarine created a market for soybean oil (34). Soybeans rapidly began to compete with other oil seeds, and cropland was shifted into soybeans. In the midwestern United States, increases in soybean production came at the expense of corn, wheat, and oat production. For the South, the soybean was a savior, replacing cotton as cotton prices plummeted in the wake of declining world demand. By 1949, the United States became a net exporter of soybeans. In less than 30 years, soybeans had become a major cash crop for U.S. farmers.

Since World War II, continuous growth in the livestock and poultry industries has further increased the demand for the high-protein soybean meal. By 1982, more than one-third of the cropland in the Corn Belt was planted in soybeans (4). The increase in midwestern soybean acreage between 1949 and 1982 is shown below. The rapidity of the spread of soybeans in the United States is significant for assessing the prospects of a successful shift to alternative crops under climate change. It demonstrates the capacity of the farming sector to convert equipment, management, and marketing to grow and process a new crop in a short period of time. It also shows the willingness of farmers to experiment with a new crop as the crop of preference (cotton, in the South) became uneconomical.

There are limits, however, to the usefulness of the U.S. soybean experience as an analogy to the shifting of crops to adapt to climate change. A major incentive to growing soybeans was the rapid growth of demand for oil and meal worldwide. The combined attributes of oil-bearing seeds and high-protein residual meal gave soybeans a clear advantage over competing crops. There do not appear to be crops waiting in the wings that could generate the kind of market that soybeans did. On a smaller scale, new crops may provide alternatives to farmers. For example, several drought-tolerant crop species, such as paloverde, jojoba, and mesquite, may be useful in dealing with increasingly scarce water in the southwestern United States (58, 102). These crops have low water requirements and produce harvestable quantities of valuable botanochemicals and other plant products.

Midwestern Soybean Acreage in 1949 and 1982



NOTE: Counties with more than 10 percent of land in soybeans.

SOURCE: Office of Technology Assessment, 1993, adapted from J.F. Hart, "Change in the Corn Belt," *The Geographical Review*, vol. 76, No. 1, 1986, pp. 51-72.

SOURCE: W.E. Easterling, "Adapting United States Agriculture to Climate Change," contractor report prepared for the Office of Technology Assessment, January 1993; Office of Technology Assessment, 1993.

Box 6-G—Adaptation to Declining Groundwater Levels in the High Plains Aquifer

The High Plains, or Ogallala, Aquifer is a large geologic formation of porous sand that underlies approximately 200,000 square miles (520,000 hectares)[1] in the U.S. Great Plains (see figure). The vast aquifer supplies water for most of this region's agricultural, domestic, and industrial uses. The response to growing water scarcity in this region may serve as a useful model for adaptation to climate change (37).

By 1980, some 150,000 agricultural irrigation wells were pumping water from the High Plains Aquifer. Use of groundwater rose steadily from 7 million acre-feet (18.6 billion cubic meters)[2] in 1950 to 21 million acre-feet by 1980 (117). In these early days of irrigation, public information about irrigation technology and the status of the aquifer was limited (118). Waste was obvious, and widespread pumping from the aquifer was causing groundwater tables to drop. Serious declines in groundwater occurred in the southern Plains, with water tables dropping more than a 100 feet (30 meters) in parts of Texas (43). in Kansas, almost 40 percent of available groundwater had been withdrawn by 1980. With declining groundwater in Kansas came increased threats to critical wetland habitats used by the whooping crane. A groundwater resource that once seemed inexhaustible appeared, by 1980, to be in danger of eventually running dry.

The Ogallala Aquifer

SOURCE: Office of Technology Assessment, 1993.

Declines in the aquifer resulted in increased irrigation-pumping costs because it takes more fuel to pump from lower depths. This increased cost has in turn prompted technical and institutional adaptations. A survey of agricultural water users across the High Plains Aquifer region found that the preferred technical adaptations to declining groundwater levels were increased irrigation efficiency and the practice of conservation tillage (51). Under conservation tillage (e.g., no-till and reduced-till management), crop stubble is left on the field after harvesting, shielding soils from sun and drying winds. A switch to low-pressure irrigation systems in the southern Plains States (53) increased irrigation efficiency by greatly reducing evaporative water losses. Overall irrigated acreage has also declined, and many farmers have switched to low-water-intensity crops such as wheat, cotton, and sorghum (66).

Institutional responses to scarcer groundwater on the High Plains have occurred at local and regional levels (48). The effectiveness of local policy has varied from State to State. Kansas, for example, passed a groundwater management law that made possible the formulation of regionally controlled groundwater management units (66). These units provide orderly development of the High Plains Aquifer with tools such as the spacing of wells, limits on numbers of wells, metering of water use, and promotion of water conservation. Areas of Nebraska have imposed similar restrictions and metering requirements. The Cheyenne Bottoms Wildlife Area of Kansas is a 13,000-acre (5,200-hectare)[3] wetland that provides critical habitat for the whooping crane and some 5 million other migra-

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1 To convert square miles to hectares, multiply by 2.590.

2 To convert acre-feet to cubic meters, multiply by 1,230.

3 To convert acres to hectares, multiply by 0.405.

(Continued on next page)

tory waterfowl that pass through each spring. The Kansas State Engineer has been able to impose restrictions on groundwater pumping in order to protect recharge rates into this wetland.

Texas, the State that could benefit most from strong groundwater governance, has rather weak groundwater management institutions (92). Unlike the other 49 States, Texas uses an absolute ownership rule in determining rights to groundwater. The rule, based on English common law, states that an owner of a parcel of land owns from the "sky above to the depths below" (92), which includes the water on, above, and below the surface. The absolute ownership rule has proved to be a formidable disincentive for landowners to agree to regulation of their water at the local level. Nevertheless, in the High Plains of northwest Texas, increasing water scarcity has resulted in innovations in the institutions for coordinating groundwater use and promoting water conservation.

The 5.5 million acres in the 15 northwest Texas counties that constitute the High Plains Groundwater Conservation District No. 1 (44) receive just 12to 16 inches (30 to 41 cm) of precipitation per year, but overlie part of the Ogallala Aquifer. Irrigation with groundwater pumped from the aquifer has allowed the region to grow large quantities of cotton, barley, sorghum, and corn for many years (74). The High Plains District was created in 1951 largely to address the needs for groundwater conservation. The District has been "dedicated to the principle that water conservation is best accomplished through public education" (44). Accordingly, the District focuses its efforts on research and demonstration projects, publishing free information about groundwater use and methods for conserving water, performing on-farm water-efficiency testing, and carefully monitoring groundwater levels and water quality.

One of the earliest District efforts was to reduce open-ditch losses. Water losses from open ditches were as high as 30 percent per 1,000 feet of ditch (44). The District performed economic analyses that showed farmers it would be cost-effective to stop losses (1 18). As of 1989, 12,097 miles (1 9,500 kilometers)[4] of underground pipeline had been laid to replace open ditches (44). Cost-effective systems for recovering irrigation tail water were also developed and demonstrated by the District (74). New technology in the form of time-controlled surge valves for furrow irrigation and low-energy precision-application (LEPA) methods for spray irrigation systems were widely demonstrated and promoted by the District. Surge valves and shortened furrows resulted in 10 to 40 percent improvements in furrow-irrigation water losses, while LEPA systems reduced center-pivot irrigation losses from around 40 percent to as low as 2 percent (W. Wyatt, ated in ref. 74; 44). In 1978, the High Plains District in conjunction with the U.S. Department of Agriculture's Soil Conservation Service initiated an on-farm water-efficiency-evaluation program. In many cases, suggested water and energy savings were sufficient to pay back farmers' costs within 1 or 2 years (74).

The High Plains District has a goal of reaching an equilibrium between groundwater withdrawals and aquifer recharge, as measured during a 5- or 10-year average. So far, net groundwater depletions in the Ogallala Aquifer underlying the District have declined from a 5-year average of 1.4 billion gallons per day (bgd) (15.3 billion liters per day)[5] in 1966-71 to an average of 0.43 bgd in 1981-86 and 0.16 bgd in 1986-91. A 25 to 40 percent cutback in groundwater use has been achieved (74); part of the cutback can be attributed to reductions in irrigated and planted area and several years of above-average rainfall (118, 44). Nevertheless, improvements in water-use efficiency and aquifer sustainability have led District officials to conclude that their voluntary, education-based approach to water conservation has been successful (44, 119).[6]

The various societal and individual responses to growing water scarcity suggest that farming regions may adapt well to a slowly changing climate. Perhaps more impressive than the ability of farmers to undertake technical adaptation has been the relative ease with which institutions have developed to promote more efficient use of scarce water resources. Still, despite the positive changes that have occurred in this region, one should not be overly optimistic. Groundwater depletion continues in much of the aquifer--even though at reduced rates-and many farmers face a reduction in future farm income as they decrease their water use.

4 To convert miles to kilometers, multiply by 1.609.

5 To convert gallons to liters, muitiply by 3.785.

6 B. Williams, Director of Administration, High Plains Water Conservation District, Lubbock, TX, personal communication, July 1992.

SOURCE: Office of Technology Assessment, 1993.

Box 6-H--Current Technologies for Adapting to Climate Change

Changes in planting and harvesting practices

Climate warming may allow farmers to plant earlier in the spring. Earlier planting could lessen the chances of damage from heat waves at critical stages of plant growth. Shifting the period when a crop's leaf area is largest so that it matches the months of maximum sunlight would increase growth rates. Earlier planting would also allow earlier harvesting because warmer temperatures speed up plant development. Earlier harvesting reduces the risks of late-season field losses. Earlier maturation may also allow grain crops to dry more completely in the field, eliminating or reducing the need for artificial drying.

Warmer springs imply a longer growing season. Early planting in combination with a longer-season cultivar may allow farmers to increase yields by taking advantage of the longer season-provided that moisture is adequate and the risk of heat damage is not too great. For risk-averse producers, earlier planting combined with a shorter-season cultivar may give the best assurance of avoiding the large losses associated with hot summer temperatures. Planting a mix of cultivars with different maturation times could increase the probability that some portion of the crop is exposed to the most favorable climate during a growing season (93).

Planting seeds deeper in the soil and reducing planting densities (plants per acre) are two simple ways of evading drought stresses. Planting seeds deeper may give them access to more moisture, which would facilitate successful germination. Smaller pfant populations reduce competition among plants for available soil moisture.

Tactics for conserving moisture

Several moisture-conserving practices have been used to combat drought and aridit y (77, 94, 97) and may be useful in adjusting to climate change. Conservation tillage is the practice of leaving the residue of the previous season's crop on the surface of the field, rather than plowing it under the surface. Conservation tillage protects fields from water and wind erosion and can help retain moisture by reducing evaporation and increasing the infiltration of precipitation into the soil. Conservation tillage also decreases soil temperature. Furrow diking is the placing of small dikes across the furrows of the field to aid the capture of rainfall. Terracing, or contouring, can be used to more efficiently trap precipitation on sloped fields. However, the construction of terraces can be costly.

Crop substitution is potentially a way to conserve moisture. Some crops require less water and tolerate warm, dry weather conditions better than others. For example, wheat and sorghum are more tolerant of heat and dryness than is corn. Microclimate modification can be achieved through the use of shelterbelts, or windbreaks. Shelterbelt systems are linear configurations of trees or tall annuals surrounding one or more sides o? agricultural fields.' They greatly reduce wind speed across the protected field, benefiting plant growth by reducing evaporative-moisture losses (77). They are particularly effective in windy regions that otherwise have little natural woody vegetation, but they are costly in terms of land use.

Irrigation scheduling is the practice of supplying crops with irrigation water only when t hey need it. It adjusts the timing of the irrigation and the amount of water to match actual field conditions. Irrigation scheduling requires sources of information about soil-moisture conditions and, when using ditch irrigation, close cooperation among farmers. A study of four Nebraska counties found that irrigation scheduling on center-pivot systems reduced irrigation-water use by 9 percent and saved farmers an average of $2.10/acre in pumping costs (8). Low-energy precision application (LEPA) is an adaptation of the center-pivot irrigation system; low-pressure application of water near ground level results in less water loss to evaporation. Trickle irrigation applies water as drops or trickles through pipes on or below the soil surface. These very efficient but high-cost irrigation systems are now in common use only for fruit crops and highly valued vegetable crops.

[1] Sunflower and corn have been used In California and Arizona, respectively, as windbreaks around highly valued crops.

(Continued on next page)

Box 6-H-Current Technologies for Adapting to Climate Change-(Continued)

Increased irrigation

Increased irrigation is one obvious means of coping with drier conditions. However, inadequate water supplies and high costs will limit this option in some regions. Regions that are currently reaching the limit of existing irrigation-water supplies (e.g., the Southern Plains and California) will be unlikely to support additional irrigation-water use (35, 69). Irrigation may decline because of increased urban competition for water and because of possible reductions or seasonal changes in the timing of stream flows. Irrigated acreage may increase only in eastern regions, where water supplies are adequate. Under a climate change, irrigated acreage as a percentage of total cultivable land could increase by perhaps 3 percent in the eastern t hird of the United States (69). The trend toward increased irrigation in the eastern United States is already under way.

Equipment purchase and increased farming intensity

Climate change may cause the quantity and quality of production inputs to change. Several agricultural experts argue that climate change may encourage farmers to alter their investments in on-farm infrastructure in order to: 1) purchase equipment necessary to change cropping systems, 2) expand the size of operations in order to offset climate-induced yield reductions, and 3) enlarge storage facilities to provide a buffer against extreme events such as drought and pest and disease outbreaks (68). Others note that farmers make investments in apparently excess equipment capacity to better ensure that farm activity can be completed before a period of unfavorable weather (90). intensification of farming in areas beneficially affected by climate can be a way to maintain overall farm yields.

Reduced farming intensity

if the frequency of poor yields increases, some farmers may reduce the amounts or quality of inputs to production (89). One exam pie would be to make fewer passes over the field for cultivation in order to hold down energy costs. Allowing irrigated acreage to revert to dryland farming or grasslands may occur when water is short or when water deiivery costs rise, as has aiready happened in the southern Ogalalla Aquifer (see box 6-G). Fallowing (holding iand out of production for a year in order to accumulate sufficient soil moisture) is often a necessary practice in dryland wheat farming. in the extreme, acreage abandonment (including not harvesting planted acreage and converting to woodlands) can be the most effective cost-cutting response to an unfavorable climate (60). Successful adaptation from t his perspective means finding t he most profitable means of farming; it does not mean that past production levels are necessarily maintained.

Helping livestock adjust

Several tactics may be used to heip livestock adjust to excessive heat (38). The temperature of animals' surroundings can be reduced by providing shade or partiai shelters. Trees make the best shade because they provide protection from direct sunlight and beneficial cooling as moisture is transpired from ieaves. During a3-day heat wave in Chino Valley, California, in 1977, more t han 700 dairy cattle died (38). Deaths in lots with adequate shade were almost 70 percent lower than those in iots where cattle had inadequate shade. Evaporative coolers that lower air temperature in animal shelters can be effective in limiting productivity losses under high temperature conditions (38). Animal wetting is an effective way to lower the surface temperature of animals. This can be accomplished with a sprinkler system controlled by a timer. Maintaining large feed reserves is another tactic that livestock farmers use to lower their risk of facing feed shortages duringclimate extremes (9).

Farm structure and marketing practices

Increasing the scale of farming operation may in some cases effectively reduce the variabiiit y in income and yields. Strategic specialization can be an advantage in a small number of safe crops (55). Efficient farming in the "safest" crop is certainly a f requent—and perhaps t he best-defense against climate risk. On dryland farms in the

Western Great Plains, where crop failures from drought occur regularly, farmers grow wheat or sorghum, using conservative and low-cost methods. To the east, where rainfall is more abundant, corn and soybeans are the dominant crops. Large-scale farming enterprises can hedge against localized climate risks by diversifying geographically, spreading their farm holdings across climate zones. In the face of increasing climate uncertainty, the value of crop diversification on individual farms through the addition of less-risky crops may increase. A 1985 survey of farmers in Florida and Alabama found that they deal with variable climate risk by keeping their operations diversified (9). The large variability from decade to decade in Illinois corn yields can be seen as an example of a response to climate change, and farmers there have responded to the perception of increasing climatic risks by diversifying.

Owners of citrus groves in north-central florida adapt to the risks of winter freezes by diversifying their source of income more than do the citrus growers to the south, whc face less risk (61). Corporate ownership or partnerships allow each investor to risk relatively little income. The fruit is often sold through vertically integrated cooperatives, rather than in on-the-spot markets, as in the south. This marketing practice allows for speedy processing of freeze-damaged fruit, a benefit that compensates for lower average prices. Changes in the structure of farm ownership and vertical integration through contractual marketing arrangements can be effective institutional ways to spread the risk inherent in farming.

SOURCES: W.E. Easterling, "Adapting United States Agriculture to Climate Change," contractor report prepared for the Office of Technology Assessment, January 1993; Office of Technology Assessment, 1993.

Ultimately, the ability of agriculture to adapt to a changing climate may be most dependent on continued success in expanding the variety of crops and techniques available to farmers. Biotechnology appears to offer hope of continued improvement in agricultural productivity well into the next century. Expected improvements in overall agricultural productivity and plants with increased tolerance to pests, drought, and heat all offer the chance for increased buffering against the direct risks of future climate change. The success of these and other potential improvements in farm management and productivity will be increasingly sensitive to how well new knowledge is transmitted to the farmer. The role of agricultural research and extension in conveying information to farmers and in promoting innovation is likely to take on increased importance under conditions of changing climate. Research must be tied to the development of information and management technologies if it is to remain a source of improved productivity (85). In the absence of such a focused effort to tie research to the needs of farmers, promised gains from new technology may not materialize.

Current Technologies for Adaptation to Climate Change

Approaches that can be used now to adapt to climate change range from changing planting and harvesting times to increasing-or decreasing—the intensity of farming (see box 6-H). Some of these approaches are technical, such as irrigation scheduling or the use of evaporative coolers to help livestock adapt to the warmer temperatures. Others involve changes in farm scale and ownership as ways to reduce exposure to risk. Still others are straightforward changes in agronomic practices, such as earlier planting or reduced tillage. These may provide the first line of defense against climate change.

Prospects for Future Technologies

The impressive past productivity gains in American agriculture do not guarantee continued technological improvement, but biotechnology, computerized management, and other technologies could usher in an era of new advances. The Office of Technology Assessment (OTA) (103) reports that projected plausible increases in annual rates of yield for major agricultural commod-

Table 6-2—Projected Annual Rates of Growth in Agricultural Yields (percent)

	Less new technology	Most likely technology	More new technology
Corn	-0.2	1.0	2.0
Soybeans	0.1	0.4	1.2
Wheat	0.8	2.0	4.4
Cotton	NA	1.7	NA
Beef (meat/feed)	0.2	0,7	1.7
Swine	1.2	1,6	2.4
Dairy (milk/feed)	0.2	0,4	0.5
Poultry (meat/feed)	0.1	0.5	1.5

NA -Not available.

SOURCE: U.S. Congress, Office of Technology Assessment, *A New Technology Era for American Agriculture, OTA-F-474* (Washington, DC: U.S. Government Printing Office, August 1992).

ities range from 0.4 to 2 percent (table 6-2), but such future advances cannot be taken for granted. Some analysts are concerned that if farmers continue to use conventional technologies, yields of many important crops (e.g., rice, corn, soybeans, and cotton) may reach their maximum potential within the foreseeable future (83, 85). Yield increases from conventional breeding and increased efficiencies in farm management should continue over the next few decades. Breeders continue to be successful in finding ways to redistribute a plant's energy into grain production rather than leaf production, for example. Other gains continue from more-intensive management and from the breeding of plants that respond well to the use of fertilizer and irrigation. Further success with these approaches may be increasingly difficult to achieve (83, 85). Although average yields achieved by farmers are still less than record and potential yields, that gap has closed steadily. Biotechnology could speed up the process of cultivar development (25), and innovative farm management could reduce the environmental costs previously associated with intensive farm practices.

Biotechnology

Biotechnology involves the use of molecular genetic tools to mod@ plants, animals, or microorganisms. By using recombinant-DNA[15] and cell-fusion techniques, scientists can isolate, clone, and study individual genes. Such knowledge allows for direct modification of the genetic structure of plants and the development of microorganisms or biochemical products, such as enzymes and hormones, that will improve the growth and performance of agricultural crops and livestock. Biotechnology does not itself provide new cultivars, but rather provides the source material for more-rapid advances through conventional plant breeding. A National Research Council study suggested that Federal support of biotechnology needs to be expanded if long-term advances are to be achieved by the time they are needed (63).

New tissue-culturing and genetic-engineering tools combined with traditional agricultural breeding methods are allowing scientists to alter plants to incorporate greater disease, insect, and weed resistance, and to better withstand environmental

An insect-ravaged cotton leaf is compared with one that has been genetically engineered with a protective gene from **Bacillus thuringiensis.**

15 Deoxyribonucleic acid.

stresses such as cold, drought, and frost. These techniques are also improving the understanding of plant resistance and are allowing the development of improved pest-control agents. Crops that exhibit increased insect resistance and herbicide tolerance are expected to be commercially available by the middle to late 1990s (103). Plants with improved resistance to diseases should become commercially available over the next decade or so.

Improved insect resistance in plants has been achieved by introducing genes that produce the toxin from the bacterium *Bacillus thuringiensis* (a natural insecticide). Some success is also occurring in attempts to develop crops that are resistant to the broad-spectrum, environmentally safe herbicide glyphosate. Soil microorganisms that can control weeds and soil-borne nematodes and insects are also being developed. All of these new ways to control pests biologically offer hope for reduced use of herbicides and insecticides.[16]

Progress in improving tolerance to water and heat stress is complicated by a lack of knowledge about the physiological mechanisms of stress. Thus, genetically engineered plants tolerant to such climate stresses are unlikely to be developed in this decade (103). Development of commercial plant varieties with improved nutrient intake (i.e., they use fertilizers more efficiently) also appears unlikely within the next two decades. A better understanding of the key roles that associations between microbes and plant roots play in the use of nutrients--often supplied in the form of fertilizers-is still needed. If nutrient uptake can be improved, a secondary benefit would accrue in water-quality improvements because fertilizer losses to surface and groundwater are a significant source of pollution problems (as well as being costly to farmers),

USDA, AGRICULTURAL RESEARCH SERVICE

Precise application offertilizers is possible using the experimental global positioning unit being installed on this tractor.

Information and Management Technologies

Future improvements in productivity may increasingly rely on the development of information and management technologies and the effective transfer of knowledge to farmers (85). Improvements in information technologies and the technology of farm management offer alternatives to the intensified use of traditional farm inputs as the basis for expanded agricultural production. Improved efficiency in the use of farm inputs and practices can increase productivity and has the potential to reduce the environmental costs associated with farming. Central to this is improved understanding of plants, animals, and farming systems, which may rely on the increased use of computers, better computer software, the use of smart machines and control systems, in-field and remote sensing, geographical information and imaging systems, and electronic networks or other communication technologies.

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16 Some fear that the development of herbicide-tolerant plants will lead to an increased use of herbicides. So far, however, efforts have&n focused on developing plants that tolerate one of the more benign herbicides, allowing less use of persistent and toxic herbicides (30). See reference 103 for a discussion of the risks related to the uses of biotechnology,

USDA, AGRICULTURAL RESEARCH SERVICE

Farmer and engineer check automated weather station that feeds data into the COMAX software system to update its prediction of cotton yield and to suggest a harvest date.

Although computers have already had an impact on farm management, they could contribute a lot more. Systems for livestock management and for access to weather and marketing information are the best-developed applications to date. The earliest new applications of computer-software technology to attain broad use may be simple "expert systems' that help the farmer diagnose and respond to very specific production problems, such as disease (103). More complete decision-support packages for farm management might begin to be available within a decade (103). Much effort is still needed in the development of crop-simulation models to support integrated-decision-management software.

The potential for the use of advanced technologies is already being demonstrated on farms that grow highly valued crops. The means exist for sensing temporal and spatial variations in field conditions and delivering irrigation water, fertilizer, and pesticides to each area of the field precisely as needed. Irrigation of highly valued crops is now automated on some farms; it relies on computer programs, soil-moisture sensors, and weather-data networks (17). Farm machinery that can selectively till, weed, or fertilize only those areas in need of attention is also being produced commercially. Widespread use of advanced agricultural technologies and computerized information services is not likely to occur until costs decline significantly and the technologies have been adapted for a wider range of production systems.

Information-retrieval systems, allowing farmers access to electronic networks and collections of farm-management information based on compact-disk read-only memory (CD-ROM), are likely to be available by the mid-1990s. The packaging of information and decision-support technology in a manner that makes it useful to farmers will be critical to enhanced farm productivity. The extension services and the private sector will need to be prepared to take advantage of the new communications techniques to deliver effective and integrated decision-support services. The USDA Agricultural Research Service has recognized the importance of research into integrated management systems and information technologies. However, research on and teaching of computer software and computer-assisted-management tools are not yet well-established in agricultural schools (103).

New *Crops and* Cropping Systems

The idea that new crops could help stabilize and diversify the farm economy is hardly new. Only a handful of crops is being readied for possible commercialization in the near future (72, 102). *Cuphea* is an oilseed that can replace imported coconut oil in soaps and detergents, but commercialization will depend on the development of varieties that retain their seeds better. *Crambe* and winter rapeseed provide erucic acid, used to produce plastics and lubricants. *Crambe* tolerates climate conditions similar to wheat. Winter rapeseed can be double-cropped, grown over the winter in the Southeast and southern Midwest.[17] Both could be commercialized quite rapidly under current conditions. Guayule produces a high-molecular-weight rubber that is well-suited for use in tires. The guayule plant tolerates the arid conditions of the Southwest, but problems with low yields must still be overcome.

Jojoba is a desert evergreen with seeds that provide a substitute for sperm oil and for some petroleum-based oils. Jojoba oil is already used in the cosmetics industry and may be useful in commercial waxes, lubricants, and polishes. Bladderpod tolerates low annual rainfall, and its seeds contain oils that substitute for castor oil in plastics production. Continued efforts in plant breeding are necessary to increase the oil content and yields. Kenaf is a warm-weather plant that produces a fiber with a cellulose content similar to that of wood. The fiber can be used in high-quality newsprint, cardboard, and high-quality paper. Late-season dryness and some salinity are tolerated, but there must be adequate water during the initial period of germination and growth. Kenaf appears to have considerable promise for commercialization.

New crops have their own drawbacks, however. It is difficult to develop new markets when existing crops or synthetic chemicals are competing for them. A limited genetic base can slow crop-breeding advances and may leave crops vulnerable to unanticipated pests and disease. By and large, new crops succeed only when they are safer and cheaper than the old or fit a unique market niche.

Several Federal programs fund research and development of new crops or new uses for existing crops. The Food, Agriculture, Conservation, and Trade Act of 1990[18] (P.L. 101-624), for example, established the Alternative Agricultural Research and Commercialization Center within USDA to provide research and financial assistance in commercializing new nonfood products from agricultural commodities. Less attention is given to new food crops because these tend to compete with existing farm products. There are, however, various food crops grown elsewhere in the world or with limited production in the United States (e.g., sorghum and various minor grains and grain legumes) that may offer opportunities under climate change. New specialty crops, multi-cropping approaches, and integrated agro-forestry


USDA, AGRICULTURAL RESEARCH SERVICE

A stand of Kenaf, a fibrous plant with potential to supplement wood-based paper pulp, is inspected at Rio Farms in Texas' Rio Grande Valley.

17 Production of canola, a spring rapeseed low in erucic acid, developed in Canada, and suitable for human and animal foods, is now expanding rapidly in the Northern Plains States.

18 Referred to subsequently as the 1990 Farm Bill.

and livestock operations may become viable future options for smaller farmers who do not have the capital to rely on high-technology farming.

THE INSTITUTIONAL SETTING

Reducing risks associated with variability in farm yields has become a central part of U.S. agricultural policy. Various institutional and structural measures are designed to support the farm sector and buffer the consumer from fluctuation in supplies and prices of farm commodities. These include commodity support programs, disaster-assistance programs, and subsidized irrigation. (See box 6-I for discussions of these programs.) In addition, the agricultural sector is supported by an extensive research and extension network.

Commodity programs are of three types: price support, income support, and supply management. Although not viewed as buffers against climate risk, the commodity programs do provide participating farmers with protection against the low prices that result from bumper-crop yields. The costs of these commodity programs are shown in figure 6-6.

The disaster-assistance programs, including disaster payments, crop insurance, and emergency loans, provide direct relief to farmers suffering weather-related losses. In recent years, Congress has provided disaster payments for losses beyond some specified percentage of normal yields (35 to 40 percent in 1992), providing partial compensation to any farmer suffering losses in excess of that amount. low-interest emergency disaster loans are available to family farmers experiencing crop losses of at least 30 percent. Individual farmers become eligible for emergency loans once their county has been declared a disaster area by the President or the Department of Agriculture. Federally subsidized crop insurance is also available to almost all farmers. Farmers may insure up to 75 percent of their average crop yield, receiving payment on additional losses if weather causes yields to fall below the insured level. Up to 30 percent of the cost of insurance is paid for by USDA. Federal expenditures on disaster-assistance programs are shown in figure 6-7.

U.S. public-sector agricultural research and extension is a dual Federal-State system that is credited for much of the remarkable growth in America's agricultural productivity. Public research expenditures in agriculture have produced high returns (32). Much of this success can be attributed to the effective transfer of knowledge to farmers and to a decentralized structure that has maintained a focus on practical research problems (82). The public agricultural research system includes the State Agricultural Experiment Stations (SAESs) and USDA's Agricultural Research Service (ARS) and Economic Research Service (ERS). The Cooperative Extension Service (CES) is the network of Federal, State, and local experts that delivers research results to farmers and feeds problems back to researchers. USDA's Soil Conservation Service (SCS) also serves a technology-transfer role, encouraging soil and water conservation in farm management. (Box 6-J discusses the USDA departments and their activities in more detail.)

Private research by food and agricultural industries and innovation by farmers have also played a significant role in sustaining agricultural productivity. Increasingly, agricultural industries are conducting their own research whenever there is the possibility for developing proprietary products. However, industry has relied on the public sector to provide funds for much of the basic research and evaluation.

Despite the strength of the overall agricultural-research establishment, there has been some debate about how well it is prepared to deal with the future (10, 73, 99). Federal funding for agricultural research has seen little or no increase (in deflated dollars) over the past two decades (see fig. 6-8). Hope for future improvements in agricultural productivity has increasingly come to rely on advances in basic science achieved outside the traditional agricultural-research struc-

Box 6-I-The Institutional Setting for Agricultural Adaptation to Climate Change

Commodity support programs

A major goal of current agricultural policy is the achievement of stability in farm incomes and commodity prices. The 1990 Farm Bill authorizes through 1995 continuation of the various commodity programs that support farm incomes and crop prices. The commodity programs are administered by the U.S. Department of Agriculture's (USDA's) Commodity Credit Corporation.[1] It provides support to producers of about a dozen commodities. The so-called ***program crops*—wheat,** corn, sorghum, barley, oats, rice, and cotton-are covered by **deficiency-payment, nonrecourse-loan** programs and by acreage-reduction programs. Other commodities, such as soybeans and other **oilseeds** (e.g., sunflower and **canola),** are covered only by the **nonrecourse-loan** programs. **Meat,** poultry, fruits, and vegetables receive no direct support. Total support expenditures of the Commodity Credit Corporation are shown in figure 6-6. The commodity programs have at times been very costly, **with** outlays reaching a high of almost $26 billion in 1989. By 1990, commodity-program payments and related expenses had declined to just over **$6 billion.** Annual **program** payments were **projected** to remain **below** $12 billion under the provisions of the 1990 Farm Bill (95). However, **FY** 1993 **payments** are now estimated at $17 billion because of bumper corn yields and high outputs of other program crops.

Price support-Price support is provided through ***nonrecourse loans.*** In essence, the Government sets a floor price (the ***loan** rate)* for covered crops-guaranteeing farmers this **price** for their crop. In practice, farmers borrow at the loan rate, with their crop **as** collateral against the loan. The loan is intended to be a marketing tool that **allows** farmers to temporarily store some of their crop and to sell it over a period of a few months, thus avoiding any glut on the market and the resulting steep drops in **market** prices. If market priis remain below the loan rate, a farmer can choose to forfeit the crop instead of repaying the loan.

Income support—income support is provided to farmers through direct payments called ***deficiency payments.*** Payment is provided whenever market prices fall below a ***target price,* which** is typically set above recent **market** prices. Deficiency payments make up the difference between the target price and the market prii (or the loan rate if that is higher). Farmers are guaranteed at least the target price for the portion of their crop that is eligible. To qualify for **a deficiency** payment a farmer **must** have planted that crop on some portion of the farm for the past 5 consecutive years. A farmer's ***crop acreage base*** for a commodity is the 5-year average of acreage planted in that crop. Only the crop acreage base is eligible for deficiency payments, with payment made on average yields from the 1981-85 period.

Supply management-Participation in the price-and income-support programs is voluntary (for most crops), although participating farmers can be required to reduce the acreage they **plant.**[2] Acreage *reduction programs,* under which some land is removed from production or is otherwise restricted in use (i.e., planted to soil-conserving crops), are set for each commodity by USDA. Acreage reduction is intended to restrict supplies, thus holding up farm prices and limiting Federal expenditures under the support programs.

A growing criticism of the deficiency-payment programs has been the inflexibility they impose on the farmer. A farmer loses base acreage and eligibility for deficiency payments when program acreage is planted in a crop other than the crop for which the farmer is enrolled. Establishing eligibility in a new crop takes 5 years of continued production. **Thus,** a farmer could sacrifice considerable income in order to **switch** crops. Previous OTA reports have noted how this has inhibited the introduction of new industrial crops (102), discouraged conservation rotations (100), and favored the production of quantity rather than **qualit** y in crops (98).

Partly in response to these concerns, the 1990 Farm Bill (as amended by the Omnibus Budget Reconciliation Act, or **OBRA,** of 1990; P.L. 101-508) introduced some degree of flexibility into the **deficiency-payment** programs.

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1 **USDA's** Agricultural **Stabilization** and Conservation **Service** (ASCS) administers and finanoes **commodlty** programs through the Commodity Credit Corporation.

2 **Certain other crops, such as sugar and peanuts, have** mandatory supply-control programs that operate **at little** or no cost to the Federal Government but d**o impose higher crests on consumers by restricting supply in order** to maintain high prices.

(Continued on next page)

Box 6-I—The Institutional Setting for Agricultural Adaptation to Climate Change-(Continued)

Farmers may now shift up to 25 percent of their crop-acreage base to the production of other crops,[3] without having that acreage removed from their program base. Under the 1990 Farm Bill, the deficiency payments are now made for only 85 percent of base acreage. On the 15 percent of the base acreage (*normal flex acres)* on which payment is not received and, optionally, on an additional 10 percent (*optional flex acres*) of the base acreage, farmers can plant most other crops without loss of their program base.[4] An increase in the normal flex acres to 20 or 25 percent is being considered in the FY 1994-98 budget reconciliation.

Disaster-assistance programs

Disaster payments-Disaster-payment programs provide farmers with partial compensation for crop losses suffered due to natural disasters or adverse weather. Since 1990, partial compensation (up to 65 percent) has been provided to all farmers for crop losses greater than 40 percent (35 percent for holders of crop insurance). Certain other permanently authorized programs, such as the livestock programs, provide assistance onty to farmers in counties that have been dedared eligible by the President or the Secretary of Agriculture.

Before 1985, various omnibus farm bills authorized continuing disaster-payment programs. Since 1985, disaster payments have been provided annually through ad hoc congressional legislation. The Federal Crop Insurance Act of 1980 (P.L. 96-365), which broadened the availability of crop insurance, was intended as the first step away from the disaster-payment programs. The Food Security Act of 1985 (P.L. 99-198) sought to further discourage the use of disaster payments as the primary means of farm risk management However, political pressures led to passage of supplemental disaster-assistance acts and appropriations for disaster payments in each year from 1986 to 1992(15). After the drought year of 1988, the Federal Government paid out nearly $4 billion in disaster payments to farmers and livestock producers (fig. 6-7). The Food, Agriculture, Conservation, and Trade Act of 1990 (the 1990 Farm Bill, P.L. 101-624) offered no new policy for disaster-assistance programs.

Critics of disaster-payment programs have argued that much of the risk inherent in farm production is unfairly transferred to the general public (e.g., see ref. 36). Past programs were also considered unfair because they were not equally available to all who suffered crop losses; only farmers growing program crops or farmers within counties declared to be disaster areas were eligible for payment. Some argue that disaster payments reduce the farmer's incentive to limit exposure to risk, encouraging production of high-risk crops in marginal areas. Such programs are thought to perpetuate marginal and inefficient farming practices.

Crop insurance-Federally subsidized crop insurance is available to almost all farmers. It provides a means for the farmer to spread the cost of occasional crop losses overtime, reducing annual fluctuations in farm income. Under the crop insurance program, farmers may insure up to 75 percent of their average crop yield, receiving payment on additional losses if natural disasters or adverse weather causes yields to fall below the insured level. Up to 30 percent of the cost of insurance is paid for by the USDA for coverage up to 65 percent. No additional subsidy is provided on extra coverage.

Federal crop insurance has been available to farmers since 1939, although restrictions on coverage limited its use until 1980. The Federal Crop Insurance Act of 1980 represented an attempt to expand the crop insurance program. Under this legislation, crop insurance was subsidized for the first time, and the eligibility for insurance

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3 There are some restrictions on the crops that can be planted. Fruits and vegetables are not allowed. Certain other crops are excluded at the discretion of the Secretary of Agriculture. These exclusions have included peanuts, tobacco, trees, and tree crops.

4 In 1991, 8 out of 41 million potential flex acres were converted from the original program crops. No deficiency payment is provided for aops grown on flex acres, although loan support is provided. The loss of deficiency payments on optional flex acreage reduces the incentive for their use.

5 Disaster payments were authorized only Acre crop insurance was unavailable. Because crop insurance was available in all counties, this essentially meant that disaster payment could be authorized only through supplemental legislation.

was greatly expanded. Despite the stated goal that crop insurance would replace disaster payments as the primary tool of farm risk management, participation in the program was disappointing.[6] The intent of the 1980 Act and the Food Security Act of 1985 to encourage the purchase of crop insurance was undercut by subsequent disaster payment programs.

Incentives to participate in the crop insurance program have been diminished by high premium rates, inadequate coverage, perceived administrative problems, and expectations of continued disaster payments (13,14). Many farmers choose instead toself-insure through savings or by otherwise acting to reduce the variability of farm income through pooled ownership or conservative management practices. The farmers who do purchase crop insurance tend to be those facing the highest risks, keeping program costs and premiums high.[7]

Even with what many farmers find to be high premium rates, crop insurance in the United States has been heavily subsidized. From 1980 to 1990, the Federal Government paid farmers $3.3 billion more than it received in premiums (96). In addition, the Government spent more than $2 billion on administrative expenses over this period. Since 1980, premiums have covered little more than 40 percent of total program costs. In 1988, the Federal crop insurance payout to farmers exceeded premium receiptsbyarecord$616 million. As with disaster payments, the unintended consequence of crop insurance has been the encouragement and subsidy of farmers most at risk.

The 1990 Farm Bill called for a move toward an actuarially sound insurance program (i.e., one with premiums sufficient to cover expected losses) but postponed the decision on a major overhaul of crop insurance and disaster assistance programs. Despite Administration and House proposals to eliminate funding, the 1991 Agricultural Appropriations Act (P.L. 101-506) maintained funding for the crop insurance program.

Low-interest loans-Emergency loans are provided through USDA's Farmers Home Administration (FmHA) to eligible producers who have sustained losses due to natural disasters. The emergency loans are offered at a subsidized interest rate to farmers experiencing crop losses in counties that have been declared disaster areas by the President, the Secretary of Agriculture, or the Administrator of FmHA. In the 1970s and early 1980s, some $2 billion of new loans were made annually under this program. In recent years, the importance of the program as a source of new loans has been greatly decreased. Eligibility is now restricted to family farms experiencing crop losses of more than 30 percent, having crop insurance, and otherwise unable to find credit. Despite the reduction in new loans, program expenses have increased significantly throughout the decade. Costs have risen (peaking at $2.2 billion in FY 1989; see fig. 6-7) because of the interest subsidy on existing loans and because of rapidly increasing default rates on earlier loans.

Subsidized irrigation water

The application of irrigation water to crops to supplement precipitation has been a powerful tool for stabilizing crop yields in the face of climatic variability in both humid and semiarid regions. The Reclamation Act of 1902 mandated several federally sponsored irrigation projects, mainly in the form of large reservoirs (36). Prices for Federal irrigation water have been subsidized at less than the full costs of storage and conveyance and well below the market value of water in alternative uses. According to the Bureau of Reclamation, almost 10 million acres of land in 17 Western States received project irrigation water in 1985 (17 percent of the total irrigated acres in the United States). The Congressional Research Service (119) estimates that the subsidy ranges from $60 to $1,800 per acre, depending on the irrigation district. Such water-pricing policies, coupled with the institutional constraints farmers face in marketing the water they do conserve, have discouraged the efficient use of irrigation water. With the increasing demand for water for nonagricultural uses, the opportunity costs of restricting Federal-project water to irrigation are increasing. (See ch. 5 for more details on water issues.)

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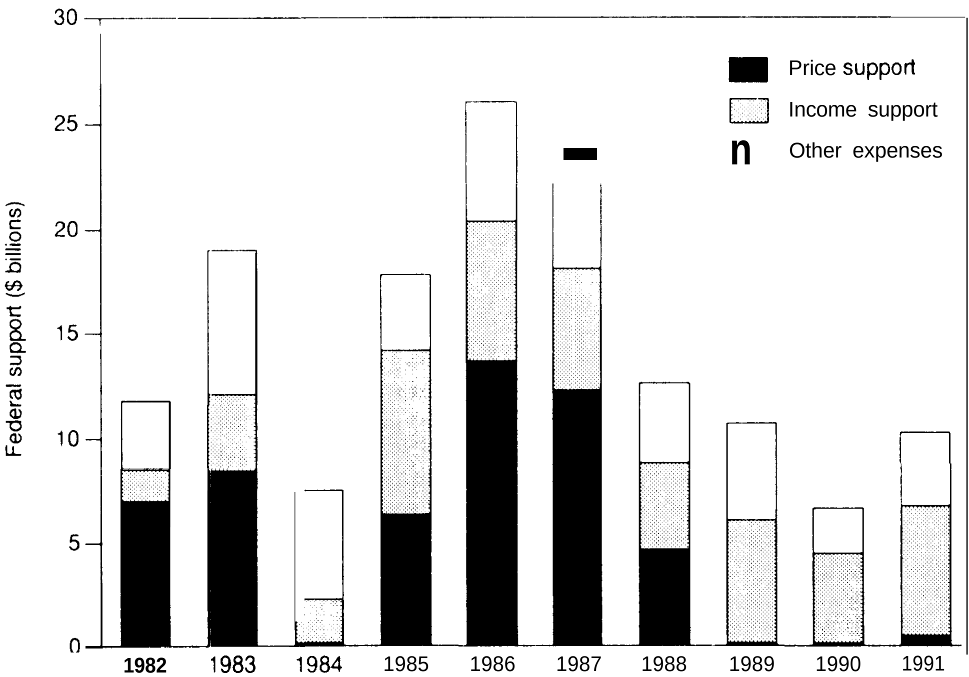
6 By FY 1988, participation in crop insurance was 23 percent of eligible acres, well below the target rate of 50 percent. In 1989, participation In the insurance program rose to 40 percent of the eligible acres. The increase occurred because many producers who participated in disaster assistance programs in 1988 were required to buy crop Insurance.

7 A recent survey in Virginia and Montana found that insured farmers were In a riskier situation than uninsured farmers. Insured farmers were less likely to have irrigation and had less income and savings and greater debt (36),

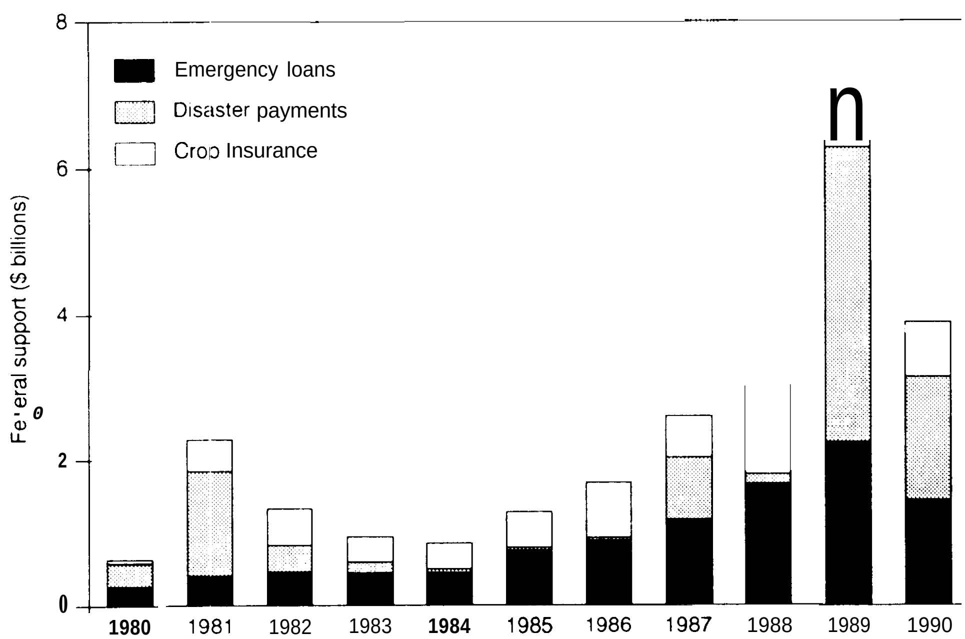
SOURCE: Office of Technology Assessment, 1993.

Figure 6-6—Net Outlays of the Commodity Credit Corporation, 1982-91



SOURCE: U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service, *Commodity Credit Corporation Report of Financial Conditions and Operations*, 1992.

Figure 6-7—Costs of Federal Disaster-Assistance Payments Over the Period 1980-90



SOURCE: U.S. Congress, General Accounting Office, "Crop Insurance Program Has Not Fostered Significant Risk Sharing by Insurance Companies," GAO/RCED-92-25 (Gaithersburg, MD: U.S. General Accounting Office, 1992).

Box 6-J-Structure of the Agricultural Research and Extension System

The Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA) conducts basic and applied research in agricultural sciences and technology and also maintains extensive collections of seeds, clonal materials, and genetic stocks of farm animals. ARS research is in such areas as environmental quality, agricultural sustainability, rural development, food safety, nutrition, marketing, soil and water conservation, and the biology and production of crops and livestock. Research is conducted at five major regional centers in Maryland, Pennsylvania, Illinois, Louisiana, and California, and at about 130 other locations, many of which are associated with universities. The regional centers are concerned primarily with the development of new products that will result in alternative markets for agricultural commodities. A national program staff is responsible for planning and coordinating the research program and for allocating funds to the agreed-upon national research priorities. Research is generally directed toward basic science that is national in significance, long term in nature, and unlikely to be adequately addressed by private or State research efforts. For example, ARS has de-emphasized the breeding of most crop varieties on the assumption that private and State efforts are adequate. Instead, emphasis has turned to genetics and the development of germ plasm that can be used by industry to develop new varieties. ARS employs approximately 2,700 scientists and research engineers and had an FY 1993 budget of $695 million. In FY 1991, ARSexpenditures on biotechnology were about $81 million, and expenditures on sustainable-agriculture research were estimated to be about $120 million.'

The Land-Grant Colleges of Agriculture were established with the passage of the Merrill Act in 1862. The Merrill Act provided Federal grants to States to fund creation of colleges that would offer practical programs of higher education focused on agriculture and the mechanical arts. In many States, the original land-grant college grew to become the foundation for the State University system. In 1890, Congress passed the second Merrill Act, which provided additional yearty Federal funds to the land-grant institutions and required that States provide college-level agricultural education to black as well white students. Seventeen Southern and border States created separate black agricultural schools.

The State Agricultural Experiment Stations (SAESs) were established with the passage of the Hatch Act of 1887. The act created the agricultural experiment stations as departments within the college of agriculture at land-grant institutions and provided annual Federal funding to support agricultural research and experimentation. Today, there are 57 SAESs, one in each State and Territory. These institutions include laboratories, field sites, and research farms. Roughly 12,000 State-employed agricultural researchers work in the network of land-grant schools and the associated Agricultural Experiment Stations. Overall, the SAES system spends about $1.6 billion (FY 1990) on research, most coming from State funds. In 1990, USDA provided $224 million to State Agricultural Experiment Stations. Other Federal agencies provided an additional $144 million in agricultural research money.[2]

The Cooperative State Research Service (CSRS) is a coordinating agency within USDA charged with dispersing Federal funds to SAES and to the State land-grant institutions. CSRS also administers grants programs that fund agricultural research. EachSAES receives Federal funds through CSRS according to a formula first specified in the Hatch Act of 1887.3 The formula funds have been valuable as a stable funding base for long-term and applied research. Additional Federal funding is provided through competitive grants to individual researchers. Competitive grants have been used to strengthen the scientific foundations of agricultural research and to direct basic scientific research to areas of national interest. These grants are based on scientific merit, as determined by

1 J. van Schilfgaarde, Associate Deputy Administrator, Agricultural Research Service, personal communication, May 27, 1993.

2 The National Science Foundation, the National Institutes for Health, and the Department of Energy are among the largest of the many other sources of Federal funds for the agricultural research stations.

3 Hatch Act funds are allocated by a formula: 20 percent of the money is allocated equally among SAESs, at least 52 percent is allocated in proportion to the State's share of overall farm and rural population, and the remainder-if not needed for administration costs—can be allocated to cooperative research between States.

(Continued on next page)

Box 6-J—Structure of the Agricultural Research and Extension System—(Continued)

a peer-review process. A third category of support is special grants, usually awarded by Congress to specific institutions for research on particular agricultural problems. CSRS employs about 155 people and had a FY 1993 budget of $482 million. Research money provided through competitive and special grants programs totaled almost $160 million in FY 1992, up considerably from the $80 million provided in 1989. The increase in funding of competitive grants reflects a shift in funding priorities toward basic sciences and away from more applied research.

The Cooperative Extension System was created by the Smith-Lever Act of 1914 to carry the results of research to farmers and rural communities. The act provides Federal funding to the land-grant colleges for extension work, a term that describes the process of taking research findings and extending them to the public through on-farm demonstrations, distribution of publications, or courses. The system includes State extension offices, now found in nearly every county of the United States; specialists located at the land-grant institutions; administrative staff on the land-grant campuses; and a USDA support program, the Extension Service. The State systems employ about 21,000 people, including almost 10,000 county agents and some 4,600 technical specialists.

The Extension Service (ES) within USDA distributes funds to the Cooperative Extension System and works cooperatively with State extension services to transfer practical results of agricultural research to landowners, farm operators, and rural communities. The Federal Government provided 31 percent of the annual $1.2 billion extension budget in FY 1990. Federal support for the extension services has been declining relative to inflation and funding is increasingly directed toward community services and rural-development programs rather than toward direct assistance for farm operators. The ES employs about 175 people and had an FY 1993 budget of $425 million.

The Soil Conservation Service of USDA serves to transfer soil and water conservation technologies to farmers. In this, they complement the transfer of production and farming-systems technology by the extension services.

The Economic Research Service (ERS) was established in 1961 to provide economic and social-science information for improving and understanding the performance of agriculture and the rural economy. ERS performs statistical and analytical research on farm-production costs and returns, commodity markets, agricultural trade, farm technologies, and the rural economy. ERS conducts policy analyses and assessments of the economic impacts of alternative agricultural policies, programs, and technologies. The research program is small, with limited funds to contract for outside research. The FY 1993 budget was $58.7 million.

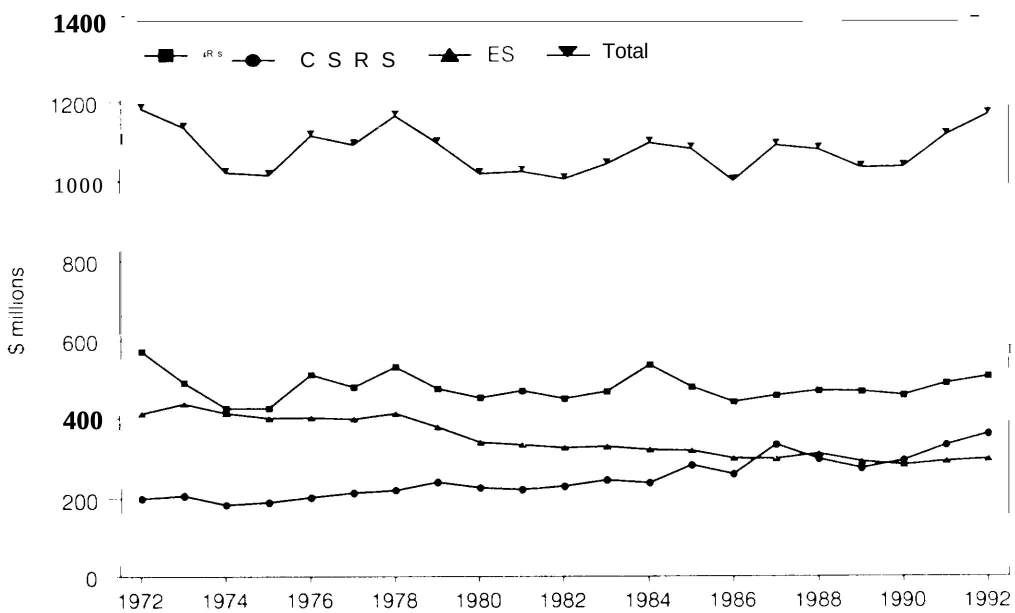
SOURCES: Office of Technology Assessment, 1993; J.M. Rawson, Library of Congress, Congressional Research Service, "Agricultural Research and Extension: Current Issues," 93-83 ENR, January 1993.

ture. **As funding goes increasingly to new and specialized areas of scientific research, traditional research addressing the day-to-day problems that plague agricultural production may be neglected (100). Federal funding for the extension services has also declined (in deflated dollars), while their mission has broadened beyond providing for the traditional family-farm constituency (73). Observers question whether the State or county extension service agents still have the expertise to assist farmers in undertaking new technologies. Encouraging basic science while maintaining an effective link between scientific research and real farm problems is a challenge that will require a broadening of the capabilities and reach of the existing research and extension system.**

POLICY OPTIONS

The resiliency of the farm sector will be enhanced by broadening and improving the choice of crops and technologies on which farmers can draw. In particular, advances that improve farm yields and efficiency in input use-that is, use of water, energy, fertilizers, pesticides-offer hope for meeting the growing demands for food and for resolving conflicts between agriculture and the natural environment. In a future that will be increasingly competitive

Figure 6-8—Appropriations for **USDA Agricultural Research and Extension Programs** for FY 1972-93



NOTE: ARS=Agricultural Research Service; CSRS=Cooperative State Research Service; ES=Extension Service.

SOURCE: J.M. Rawson, Library of Congress, Congressional Research Service, "Agricultural Research and Extension: Current Issues," 93-83 ENR, January 1993.

and uncertain, the roles of the educated farmer and of the agricultural research and extension services in speeding the transfer of knowledge to farmers become more important. The potentially high costs of climate change can be reduced by improving the capability of farmers to successfully adapt.

The ability of farmers to adapt to climate change may be constrained by several factors: 1) inflexibilities imposed by commodity support programs, 2) inflexibilities in disaster-assistance programs, 3) increasing competition for scarce water, 4) technical limits to increased productivity, and 5) an inadequate framework for planning the long-term needs of the agricultural sector. Each of these factors and related policy options are discussed below.

Commodity Support Programs

Commodity support programs are designed to stabilize farm supply and maintain farm incomes (see **box** 6-I). The means by which they currently do this may discourage the changeover from one cropping system to another that is better suited to a changed climate. For example, if climate change creates a situation in which crops are shifted to the north, the financial penalties imposed under current programs on farmers who change crops will slow the rate of adjustment and so add to the cost of climate change (54). On the other hand, if elevated CO_2 results in enhanced crop yield but no shift in range, there may be more-frequent bumper crops and low commodity prices, but substantially higher costs in farm-income support.

The deficiency-payment programs result in the greatest disincentive for farmers to switch crops (see box 6-I). First, crop choice is often driven by the level of support payments rather than by market prices. Relatively high target prices, such as those seen in the past decade for corn, discourage a switch to crops that might otherwise be more profitable at market prices. Second, because support is linked to establishing and maintaining a record of continued production in a particular commodity, farmers are penalized when they do switch crops. With the distortion of underlying market-price signals and penalties for crop switching, farmers may persist in growing crops that are not well suited to changed climate conditions. The public will bear the costs of this misallocation of productive effort through higher commodity prices or program costs.

The deficiency-payment programs have also been criticized for discouraging sound management and leading to an expansion of farming into marginal lands, many of which are highly erodible or otherwise environmentally sensitive.[19] Because traditional rotation. crops such as leguminous forages, are not covered by any support programs and detract from the acreage in program crops, farmers are discouraged from engaging in sound rotation practices (100). This exacerbates erosion and encourages the use of chemical fertilizers.

Equally serious are the problems that result from coupling deficiency payment to farm yields. Because deficiency payments are directly related to output, farmers have a strong incentive to maintain high yields through the intensive use of farm chemicals. The price subsidy also encourages an expansion of agriculture into marginal lands. At the same time, under the Conservation Reserve Program, the Wetlands Reserve Progam, and various water-quality incentive programs, farmers are paid to remove erodible lands from production and to reduce environmental damages. This is why the farm programs have been compared with 'driving a car with one foot on the gas and the other on the brake."[20] The expansion of farming into marginal lands and the discouragement of conservative farming practices expose the public to risks of higher program costs and greater disaster-assistance needs under climate change, along with the likelihood of increased environmental damage.

Partly in response to these concerns, the 1990 Farm Bill as amended by the Omnibus Budget Reconciliation Act of 1990 (P.L. 101-508) introduced some degree of flexibility into the deficiency-payment programs. Farmers may now shift up to 25 percent of their program acreage base to the production of other crops, without having that acreage removed from the program base-that is, from the total acreage used to calculate their benefits. On 15 percent of the base acreage *(normal flex acres),* there are no deficiency payments but the farmer is free to switch to other crops.[21] An additional 10 percent of the base acreage *(optional flex acreage) may also be* switched to other crops, but deficiency payments are lost if the land is planted in other crops (see box 6-I). As a budget-reducing measure, an increase in the normal flex acres to 20 or 25 percent is being considered in the FY 1994 budget reconciliation.

Policy Options: Commodity Support Programs

Option 6-1: *Allow fiull flexibility (normal crop acreage). The* Bush administration and others have suggested that farmers be allowed to grow any program crop they choose on all acreage normally planted in program crops and be eligible for deficiency payments on whichever crop is grown. This approach, known as normal crop acreage (NCA), eliminates most of the inflexibili-

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19 Previous OTA reports have noted how this inflexibility in farm programs has inhibited the introduction of new industrial crops (102), discouraged conservation rotations (100), and favored the production of greater amounts of-rather than higher-quality—crops (98).

20 Senator Rudy Boschwitz, R-MN. Address presented at a conference held by the Center for the Study of Foreign Affairs, Arlington, VA, Nov. 25, 1986.

21 There are some restrictions on tine crops that can be planted. Fruits and vegetables are not allowed, and certain other crops are excluded at the discretion of the Secretary of Agriculture. These exclusions have included peanuts, tobacco, trees, and tree crops.

ties in crop selection.[22] However, fully **reducing the inflexibilities also requires an adjustment in the methods by which target prices or farm-income-support payments are set, perhaps by making farm-income support independent of crop production. Without this, crop choice will still be largely driven by target prices, and not responsive to climate change. Congress could incorporate the NCA approach into the definition of the farmer's base acreage in the 1995 or subsequent farm bills.**

A concern with the NCA approach is that it reduces USDA's control over the supply of individual crops because acreage set-aside requirements can no longer easily target specific crops. This lack of control raises concerns about increased instability in farm prices. Farmers now growing crops without program support have expressed concern that they will be unfairly exposed to new competition from supported farmers who switch crops (participation in most commodity programs is voluntary). Another concern is that farmers' crop choices may still be driven largely by the target prices set for individual crops, thus limiting responses to climate change and market prices. To deal with this, some uniform method for setting target prices is needed. Alternatively, the current deficiency-payment programs could be replaced with an income-support program that is not coupled to crop production.[23]

Option 6-2: *Increase flex acreage. The flex-***acreage** approach appears to have been successful in introducing some flexibility in crop choice[24] and in reducing the potential costs of commodity programs (through the elimination of deficiency payments on normal flex acres). Congress could gradually increase normal or optional flex acreage in successive farm bills, further adding to farmers' flexibility in crop choice.

Normal flex acreage could **be** increased to at least 25 percent in the next farm bill. Because deficiency payments are withdrawn on normal flex acres, the costs to the Government of commodity programs would also be reduced.[25] Subsequent farm bills could further increase normal flex acreage. Gradually phasing out farm support in this manner appears to follow the direction set by the 1990 Farm Bill, avoiding the substantial difficulties associated with any full restructuring of commodity programs. However, linking increased flexibility to reduced farm support may prove hard for farmers **to accept.**

An alternative would be to increase optional flex acreage. So far, however, farmers have shown little interest in using the optional-flex-acreage allowance because program support is lost when the acreage is planted to new crops (an indication of how much the support programs do influence the behavior of farmers). Still, an increase in the optional flex acres may offer somewhat more flexibility than now exists, allowing farmers to respond to significant changes in market prices and growing conditions. A farmer who uses optional flex acres maintains eligibility for program support, regaining support if the land is replanted to the program crop. This protection somewhat reduces the risks involved in changing cropS.

■ Disaster-Assistance Programs

Periodic losses caused by climate variability are inherent to farming. Farm prices, land values, and farming practices adjust so that farmers, on

22 The NCA approach was briefly used by USDA in 1978 and 1979. Although there is little indication that there were any fundamental problems, it was later abandoned by the agency and the Senate Agricultural Committee. See reference 29 for details on NCA programs.

23 See reference 28 for discussion of proposals to decouple farm-income-support payments from yields. Even with payments that are unrelated to farm yields, any subsidy will tend to encourage a higher level of farming activity than would otherwise be profitable (28). Farmers have been reluctant to accept income support that is independent of farm yields, perhaps fearing that such an approach seems more like welfare.

24 In 1991, 8.3 of 41.3 million potential flex acres were converted from the original program crops.

25 It appears likely that as a budget-cutti.rlg measure, normal flex acreage will be increased to 20 percent under the 1994 Budget Reconciliation Bill.

average, are adequately compensated for climate risk under competitive market conditions. Subsidies and disaster assistance have distorted the market, encouraging expansion of farming into marginal lands and reducing incentives to undertake safe farming and sound financial practices (54). Much of the burden of increased risk-both the monetary costs and any environmental costs associated with conversion of marginal lands to farming-is placed more broadly on society. The Australian Government, faced with similar concerns, is moving to eliminate all agricultural disaster payments and to replace them with programs that encourage self-sufficiency and information on sound farming practice (116).

The costs of disaster-assistance programs (crop insurance, disaster payment, and emergency loans; see box 6-I) can be expected to rise if climate change leads to more-frequent episodes of drought and related crop losses. The subsidies provided by these programs reduce farmers' incentives to recognize and adapt to increasing climate risks, which imposes further costs on the general public. Reducing these subsidies will better prepare the farm sector to respond to changing climatic risks and should also prove beneficial in reducing conflicts between agriculture and the natural environment.

Society does benefit from stable food prices, and well-designed risk-spreading programs contribute to this stability. Disaster-assistance programs should be restructured-not eliminated—to encourage farmers to limit their exposure to climate risk and thus to lower the costs of the programs to society.

Policy Options: Disaster-Assistance Programs

Option 6-3: *Define disasters formally, with assistance provided only for unusual losses.* Congress could formalize the criteria for receipt of disaster payments and eliminate the crop insurance program. Currently, disaster-payment programs are provided each year in ad hoc legislation passed in somewhat pressured situations and driven by immediate needs. It is unlikely that disaster payments will be eliminated. Farmers have come to rely on this protection, and Congress faces considerable pressure to provide it. If requirements for disaster-payment programs were form W, some of the more undesirable features might be controlled. For example, all farmers could be provided with free coverage against truly catastrophic climate events, but otherwise would receive no disaster payments. With this change, farmers' incentives to undertake precautionary farm-management and financial practices could be greatly increased, and buffering against climate change risks would be improved.

Currently, disaster-assistance programs compensate farmers who have experienced crop losses of at least 35 to 40 percent. Partial compensation is received for losses greater than that amount.

- Congress could set the trigger for compensation to a level that is less frequently exceeded (say, a loss of 55 or 60 percent).
- Alternatively, coverage could be eliminated for farmers who have repeated losses. For example, farmers might be limited to receiving payments two times within any 10-year period.

A permanent disaster-payment program could be authorized, providing payment to any farmer who experiences significant weather-related losses. With universal coverage, potential inequities that result if eligibility is limited to farmers in declared disaster areas are removed. One of the strongest objections to eliminating crop insurance (that to do so strips farmers of individual protection against climate risks) would thus be removed. However, with a permanent and universal program of disaster payments, expenses might become less controllable.

- To reduce budget expenses, farmers or farm counties could be required to contribute to a disaster-assistance fired in order to be eligible for disaster payments.

Recent disaster-payment programs have set payments based on losses relative to "normal" production. This is usually based on average yields over a period of years, with extreme yields (either high or low) excluded from the average. It would seem unwise to exclude ''abnormal' years from the average if climate change is in fact altering normal climate.

- Congress could require that a moving average of crop yields over the past 5 years be used to determine normal output.

Option 6-4: *Combine disaster-payment and crop insurance programs.* Congress could combine disaster payments and crop insurance, giving all farmers free catastrophic-loss coverage (partially compensating for losses beyond some high limit) and offering additional coverage to those who are willing to pay. The Federal Crop Insurance Reform Act of 1990 considered by the 101st Congress would have provided such a combined disaster-assistance program. All farmers would have received disaster protection for losses exceeding 50 to 70 percent (depending on participation in other farm programs), The crop insurance program would have remained essentially unchanged, with subsidized coverage available for crop losses greater than those covered by the catastrophic policy.

Proponents of the plan argued that it would eliminate the pressure for supplemental disaster legislation and would encourage farmers to protect themselves against ordinary climate risks. Opponents were fearful of the potential costs. Although administrative expenses and the insurance subsidy would be largely unchanged, expenditures on disaster payments could increase with universal coverage. Opponents also expressed concern that the proposed plan would eliminate any chance of making the crop insurance program sound.

Option 6-5: *Improve the crop insurance program. In* principle, crop insurance provides an attractive mechanism by which farmers can reduce the inherent variability in farm income. However, few would argue that the goals of the Federal crop insurance program have been met. Participation is limited, program costs are high, and disaster payments remain a primary cushion against climate risks. Because of the high cost of insurance and the expectation of continued disaster payments, participation in the crop insurance program is primarily limited to farmers in high-risk areas.

Several potential reforms of the crop insurance program were suggested to Congress during debate of the **1990 Farm Bill (13, 14).[26] Some analysts and researchers have sought to reduce subsidies on crop insurance, hoping to make the program actuarially sound (i.e., self-supporting). Many have sought to encourage greater program participation through increasing subsidies, reducing deductibles,[27] improving administrative procedures, modifying in the means by which losses are calculated, or requiring crop insurance for eligibility in other farm programs. A more radical reform would combine crop insurance and income-support programs into a revenue insurance scheme that would guarantee a minimum farm revenue.**

Congress could choose to revisit the many reforms that have been suggested in the past. The success of any reforms in the crop insurance program would be contingent on expanded participation, which would allow crop insurance to replace disaster payments. The resulting restructured program might then offer both improved risk management and reduced costs over the current combination of crop insurance and disas-

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X The Federal Crop Insurance Commission Act of 1988 (P.L. 100-546) authorized the formation of a 25-member commission to identify problems with the crop insurance program and to make recommendations for increasing farmer participation.

27 The highest level of coverage that can be purchased requires farmers to absorb the first 25 percent of losses. Many farmers consider such losses sufficiently rare that insurance is an unneeded expense.

ter assistance programs. However, if **greater participation is achieved through higher subsidies and lower deductibles, these benefits might well be lost.**

Option 6-6: *Provide a self-insurance program for income stabilization.* **Congress could consider a program modeled roughly on individual retirement accounts (IRAs), under which farmers would be encouraged to self-insure against climatic risks. The program could be supplemented with catastrophic coverage either through crop insurance or disaster payments, and it would allow farmers to smooth the fluctuation in their income over time.[28] Farmers would be allowed to set aside income, tax-free, into a self-insurance account. Annual deposits up to a maximum amount (say, $15,000) would be allowed, with no further deposits allowed once the account reaches some maximum cap (say, $150,000). The cap would encourage active use of the account for income smoothing, and the tax-free status would encourage participation. Withdrawals could be made at any time, subject to income tax payment at that time (with no penalty for early withdrawal, in contrast to the IRA model). Existing disaster programs might be gradually phased down, until they provide only protection against truly catastrophic events.**

Water-Use Efficiency

Many climate-change forecasts suggest that agricultural regions of the United States could become hotter and drier, so efficient use of irrigation water might be required to maintain farm production (see box 6-I). Farmers who can manage water efficiently would be better prepared to respond to harsher climate conditions. Unfortunately, many farmers have little incentive to conserve water **because** of subsidized prices, inadequate institutional arrangements for regulating access to groundwater, and limited marketability of conserved water. Farmers who receive water from Federal irrigation projects generally pay less than the water costs (see box 5-F). The subsidized price encourages high levels of agricultural water use. Farmers who do conserve water may be inadequately rewarded for doing so or may actually be penalized under some State laws. Water saved may even be forfeited.

Policy Options: Water-Use Efficiency

Chapter 5 provides a thorough discussion of water issues. Agricultural water use is one component of several broader options discussed in that chapter. Among them are the options involving: 1) reform in pricing in Federal water projects (option 6-7, or 5-5), 2) clarification of reclamation law on trades and transfers of water (option 6-8, or 5-7), and 3) reform of tax provisions to promote conservation investments (option 6-9, or 5-4). Incentives for installing efficient **irrigation equipment** and for undertaking water-conserving farm-management practices could be implemented through direct subsidy or in exchange for eligibility in existing commodity-program **or water** subsidies.[29] Soil Conservation Service standards for soil suitability and irrigation efficiency could be used to determine eligibility for incentive programs (see ch. 5 for details).

Agricultural Productivity

Broad-based research directed at enhancing the long-term basis for increased agricultural yields is an essential element of a public research strategy. Public efforts should be directed at those areas not adequately handled by the private sector. In other words, the Federal effort may be best directed at basic science, long-term or high-risk technology

28 Before the Tax Reform Act of 1986 (P.L. 99-514) was passed, taxes could be computed on the basis of "income averaging." Farmers, who regularly experience fluctuating incomes, have felt they were unfairly treated by the elimination of this provision (31). The approach offered here provides the benefits of income averaging, plus a strong incentive to actually smooth fluctuations in income.

29 Subsidies that lower the capital cost of installing new irrigation equipment may encourage conservation by farmers already using irrigation; they could also lead to the undesirable outcome of more overall irrigation. This should not be an insurmountable problem.

development, and other areas where private profit is limited but public value is high. Biotechnology and related genetics research may offer at least a partial solution to the problem of sustaining the ability to produce food over the long term. Continued public research is needed to build an understanding of the genetic and biological bases of nitrogen fixation, drought and heat tolerance, and pest and weed resistance. Efforts are needed in the development of new germ plasm that could be the basis for subsequent commercial development of plant varieties. Protection of existing germ plasm in traditional and nontraditional crops is also important because it ensures the ability to develop new crops and strains in the future.

Conventional breeding efforts should not be ignored as a source of productivity gains in the near term. The ability to manipulate complex genetic characteristics through biotechnology remains limited.[30] For example, conventional breeding may offer the best immediate hope for improving drought and heat tolerance in crops. Efforts to expand the diversity of available cultivars through crop breeding may provide insurance against an uncertain future climate. Attention to the development and commercialization of new crops may become more important in a future under which climate change might threaten the competitiveness of traditional crops. Public efforts will be needed for those crops and market or climate niches that receive little attention from commercial breeders. It may be important to develop crops and cultivars that are adapted to warmer or drier climate conditions. Efforts toward developing cultivars that require small amounts of farm chemicals would help relax the environmental constraints that might otherwise limit expansion of farm output.

Equally important are efforts to enhance the knowledge and skills of farmers and the technology of farming. Farmers face a future in which they must be increasingly responsive to world competition, environmental concerns, and the uncertainties of climate change. The competitiveness of the U.S. farm sector will increasingly come to rely on its ability to farm with greater skills than the rest of the world. One of the most important attributes of future technologies will be the ability they give farmers to deal with unanticipated changes. Information and management technologies in the form of computer software, sensors, robotic and control equipment, and other packaged-knowledge products can provide this flexibility. These *intelligent* farm technologies offer the potential for substantial gains in efficiency of farm management and for reductions in agriculture's undesirable environmental consequences. The role of technology transfer also takes on increased value under a changing climate. If farmers are to adapt to any sort of change in a timely manner, efforts must be made to provide them with accurate, convincing information on the effectiveness of new farming systems, crops, and technologies. The private market may respond to meet some of these needs, but a public role seems imperative.

Policy Options: Agricultural Productivity

Option 6-10: *Enhance research on and development of computerized farm-management systems.* Congress could act to enhance the role of the Agricultural Research Service (ARS) as the center of excellence in design and integration of new information and management technologies into farm-management systems. Increased competitive-grant funds could be provided to universities and private researchers to carry out the research needed to fill critical knowledge gaps that are barriers to delivery of new agricultural technologies to the farmer.

The potential to develop and expand the use of intelligent information and management (i.e., using land-based or remote sensors, robotics and controls, image analysis, geographical informa-

[30] At the least, it should be recognized that the benefits of biotechnology will ultimately be put in place through the efforts of plant breeders.

tion systems, and telecommunications linkages-packaged into decision-support systems or embodied in intelligent farm equipment) to improve crop and livestock production and farm-resource management is considerable. Tractors are now produced commercially that can plant, till, or apply chemicals as needed to specific areas of a field. There are also commercial packages (including computer hardware and software, sensors, and telecommunications linkages) that can control irrigation and provide decision support for fertilization and pest-control application. Only farmers growing the highest-valued crops (such as fruits and vegetables) can afford these systems now.

Long-terrn public funding has been essential to the development of the few existing commercial packages. Enhancing these systems and reducing equipment costs to allow broader application will require considerable research and development effort. ARS proposed a program of research on intelligent farm-management systems under the Federal Coordinating Council for Science, Engineering, and Technology's (FCCSET'S) 1994 Budget Initiative on Advanced Manufacturing. ARS expects that $1 million will go to integrated, or intelligent, farm-management-systems research. ARS had initially hoped for a larger role in the FCCSET initiative, sufficient to provide $6 million for intelligent farm-management-systems research. The strategic plan for the State Agricultural Experiment Stations also considers this a high-priority area for new research, suggesting a need for $47 million in new funding (33). No other single area was considered to need this large a funding increase.

Option 6-11: *Improve the research and extension process by expanding farmer input.* Congress could support an expanded role for farmers in assessing the effectiveness of farming practices and in disseminating results of research on innovative farm practices. A broad-based program of grant support for systematic on-farm experimentation and a database on farmers' financial successes and failures under different farming systems could help farmers adapt to climate change.

Farmers are most convinced by the success of other farmers-rather than by information from experiments conducted on university lands under ideal management conditions. State experiment stations have already found that demonstration plots on farms are excellent teaching aids and succeed in getting farmers to more quickly adopt certain practices. The willingness of farmers to take up new techniques (including techniques designed to reduce the environmental costs of farming) could be further enhanced if farmers were more extensively included in the research, experimentation, and infornation dissemination process.

- Support on-farm experimentation. Abroad-based program of support for on-farm experimentation in new cropping practices would be useful in providing the information that would help farmers adapt to climate change. A model that could be built on for this purpose can be found in the Sustainable Agricultural Research and Experiment (SARE) program funded under the 1990 Farm Bill (see box 6-A). Under this program, Federal funding is provided to experiment stations to support farmer participation in research and on-farm demonstration projects. One possibility is to pay farmers for conducting field tests to demonstrate the success or failure of new farming systems in real-world situations, working with experimentstation, Soil Conservation Service (SCS), or extension-service personnel.[31] Farmers could be compensated if they bear the risks of trying unproven technologies.
- Develop a database on successful practices. In conjunction with a program of

[31] Usually, only nominal rents must be paid for setting up experimental plots on farmers' fields. The State of Illinois has found it cheaper to use farmers' fields than to own cropland and has been able to sell some research facilities as a result.

on-farm experimentation, there could be support for a wider program of recordkeeping to establish a database on the financial successes and failures of farming systems. An easily accessed database, giving farmers access to records and information on successful farm-management practices, could help speed adoption of successful practices. Such databases could be developed and maintained at State experiment stations (or distributed on compact disk) and be made accessible by phone line to personal computer users, Software that could provide easy access to the database and efforts to organize the database into a useful format would be required. Cooperative support for farmer-initiated networks and information exchanges might be another way to increase the efficiency with which farmers accept innovations in farming practices,

Option *6-12: Support agricultural biotechnology and genetics.* Congress could maintain or increase funding for regional centers of excellence in agricultural genetics and biotechnology research. Increases in competitive grants in areas of particular interest could be used to direct the research effort. Areas of obvious long-term national interest include programs addressing the understanding of photosynthetic efficiency, nitrogen fixation, tolerance to heat and drought, and the development of crops that require reduced herbicides or pesticides. Although climate change does raise the importance of research about drought and heat tolerance, this area should be promoted in tandem with pursuing broader gains in productivity, where the probability of success and the ultimate payoff may be higher.

Option 6-13: *Support conventional crop-breeding programs.* Congress could encourage USDA to sustain or increase public, conventional crop-breeding efforts. Crop breeding offers the most immediate hope for providing improved cultivars that are adapted to particular climatic niches. This may be especially so given the number of ‘‘wild” varieties that have yet to be studied and that could improve the existing domestic crops. Efforts at expanding diversity in cultivars are not adequately supported by the private sector unless investors anticipate profitable markets. Conventional breeding is also considered necessary for the maintenance of desirable cultivar attributes. One consequence of ignoring this maintenance effort can be an increased need for pesticides to compensate for declining resistance to pests. This unglamorous side to breeding has been underfunded. Further, breeding of minor but potentially valuable crops, such as forages, small grains, and oats, may be getting too little attention from either the Government or the private sector.

Option *6-14: Increase support for the development of new commercial crops.* Development and introduction of new commercial crops can be a slow process. Successful commercialization relies on a combination of farmer and market readiness that may be difficult to achieve. Availability of new crops might provide U.S. farmers with opportunities to diversify to counter the threat of climate change or a chance for profitable specialization. Congress could expand ongoing USDA research aimed at improving the commercial characteristics of several promising alternative crops. Priorities should be given to crops for which there are potentially profitable markets and perhaps to crops suited to hot or dry conditions. Congress could authorize assistance to businesses to establish crops and product markets, once the development of commercially stable varieties has been demonstrated.

Planning Needs

By improving the process of agricultural resource assessment and program evaluation, USDA could improve its ability to develop responses to major issues like climate change. A model might be the program and assessment process that is undertaken by the USDA Forest Service under the Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974 (P.L. 93-378). (See vol.

2, ch. 6, for a more complete discussion of OTA'S RPA assessment.)

USDA currently provides periodic assessments of agricultural soil and water conditions and trends under the appraisal process, authorized by the Soil and Water Resources Conservation Act (RCA) of 1977 (P.L. 95-192). Despite the considerable background effort that goes into these analyses, the assessments are narrowly focused on the specific concerns of USDA's Soil Conservation Service. With little extra effort, USDA could provide a full assessment of trends in the agricultural resource, farm ownership, rural economic conditions, agricultural technologies, supply and demand, and the impact of farm programs and subsidies. Included in this evaluation could be an assessment of climate change as one of many possible significant future disturbances to supply and demand, as the Forest Service has been doing. On the basis of this assessment, USDA could develop a program document that clarifies the agency's direction and justifies its programs as a whole.

Policy Option: Planning Needs

Option *6-15: Broaden the focus of the current Resources Conservation Act appraisal.* Congress could **amend the current authorization for the RCA appraisal process, creating a new agricultural program and assessment process modeled** on the RPA program and assessment of the USDA Forest Service. As in the Forest Service, the assessment should be made by staff members who are not tied to a specific: action agency within USDA (currently, the RCA is tied to the Soil Conservation Service).

FIRST STEPS

If public policy aims to ensure that U.S. agriculture can adapt to climate change and maintain its competitiveness in world markets, there is a wealth of policy options, as outlined above. However, the most pressing targets for policy appear to be:

- **—removing the impediments to adaptation that are created by commodity support programs, disaster assistance, and irrigation subsidies;**
- **—improving technology and information transfer to farmers in order to speed the process of adaptation and innovation in farm practice; and**
- **—supporting research and technology that will ensure that the food-production sector can deal successfully with the various challenges of the next century.**

The agricultural sector of the U.S. economy is already unusual in the great amount of public money spent in support of research, development, and technology transfer. The steady stream of technological improvements that have resulted has allowed the United States to feed a growing world population at increasingly low cost. In recent yearn, the focus has shifted away from how effective the effort has been, pointing instead to the expense of farm programs and the environmental consequences of intensive farming. However, if the United States wants to remain competitive in the world market even though rapid population growth is increasing the demand for food while biological limits to productivity growth seem ever closer, public efforts to support the continued growth in agricultural yields remain necessary. With its technological and institutional strengths, the Nation should be in a position to enhance its role in a growing world agricultural market. But in the competitive world market, success will rely on continued improvements in productivity and on the skills of U.S. farmers as they innovate and adapt to changing market conditions.

Climate change adds to the importance of efforts to increase agricultural productivity, to improve the knowledge and skills of farmers, and to remove impediments to farmer adaptability and innovation. Efforts to expand the diversity of crops and the array of farm technologies ensure against a future in which crops or farming systems fail. Efforts to enhance the adaptability of farmers—to speed the rate at which successful farming

systems are adopted--can lower the potentially high costs of adjusting to climate change.

All of the options described in the previous section are of some value if implemented today, even if no climate change occurs. Many options, particularly those related to research and extension, are being pursued to some degree. Others, such as the options to modify commodity support programs, disaster assistance, and irrigation subsidies, have been much discussed. In general, climate change strengthens the case for actions already being considered or underway rather than suggesting new directions of effort.

Several of the options we have suggested should be addressed promptly. Research on information and management technologies is important now because of the time needed to develop and implement new technologies and because of the lack of effort now being made (33). Modifications to the farm commodity program are included as first steps because there appears to be a window of opportunity to implement changes. Disaster programs fit in much the same category; frustration with current programs makes some political action likely. The difficulty experienced in redesigning the agricultural programs suggests all the more that these reforms be placed on the agenda early so the process of change can begin. Although conventional crop breeding has not been included in the list of first steps, it is an area that merits more attention. Efforts to improve or maintain the desirable cultivars appear to be underfunded for many crops-as more glamorous research areas have attracted public funds and private efforts have focused on larger markets.

Some areas of obvious concern, such as biotechnology research and new-crop development, have not been included as first steps. This is not because they are unimportant or not urgent, but rather because there is considerable effort under way already. Improvement in the effectiveness of the extension process, through more deliberate inclusion of farmers and better dissemination of data, may ultimately be of great importance. However, there seems to be little cost to waiting before implementing such actions. Perhaps most important here is that existing technology-transfer services should not be allowed to decline to the point that they cannot be rebuilt. Institutional changes that will encourage the conservation and efficient use of irrigation water will also be important in buffering agriculture against the threat of climate change. (See ch. 5 for a discussion of water issues.)

- **Revise the commodity support programs to encourage responsiveness to changing climate and market conditions Congress addresses farm issues every 5 years in omnibus farm bills, with the next one likely to be debated for passage in 1995. The annual budget-reconciliation process and agricultural appropriations bills offer intermediate opportunities for revisions in commodity support programs. The high expenditures on commodity support programs and the previously successful implementation of the flex-acreage program have made it very likely that flex acreage will be increased in the current budget-reconciliation process. This revision provides the opportunity for reducing expenditures on commodity support and increasing the adaptability of farmers to climate change. A further increase in flex acreage or other more substantial revisions in commodity programs (e.g., introduce normal crop acreage) would probably have to be considered in the 1995 Farm Bill.**
- **Use the 1995 Farm Bill to modify disaster-assistance programs. Since the late 1970s, Congress has been considering how to best structure the crop insurance and disaster-payment programs. After a flurry of proposals and studies before the passage of the 1990 Farm Bill, the programs were left essentially unchanged. There is, however, an ongoing sense of frustration with the current system that suggests that major revisions are likely to be considered in the 1995 Farm Bill. It remains unclear what the best option is for**

revising these programs. However, any program that provides a. greater incentive for farmers to reduce their exposure to risk should help in preparing for the risks of a climate change. Features of a restructured system might include:

-defining disasters formally, with assistance provided only for unusual losses;

-eliminating either crop insurance or disaster payments (i.e., do not have one program undercut the incentives to participate in the other);

—limiting the number of times a farmer could collect disaster payments; and

—requiring farmers to contribute to a disaster-payment fund (payment could be related to past claims), thus providing an incentive to reduce exposure to risks.

■ Enhance the agricultural technology base. Congress could act to enhance research in computerized farm-management systems. The competitiveness of the farm sector will increasingly depend on technological advances that improve the efficiency of U.S. farmers-rather than on further increases in mechanization and intensity of input use. Computerized farm-management systems will be increasingly important to the farmer's ability to increase yields, control costs, and respond to environmental concerns. Limiting the runoff and leaching of farm chemicals depends most on careful timing of application and on applying only what is needed.

ARS has suggested that about $6 million annually would allow considerable improvement in its current program.[32] Funding this full $6 million program or similar support by Congress would provide for the development and broader use of technologies that have the potential to greatly enhance the efficiency of farming and increase the flexibility with which farmers can respond to climate conditions. ARS already provides leadership in this area.

AGRICULTURE—FIRST STEPS

- **Revise the commodity support programs**
  —Increase flex acreage or introduce normal crop acreage in the 1995 Farm Bill to allow farmers to switch crops without penalty.
- **Modify disaster-assistance programs**
  —Formalize requirements for disaster payments in order to encourage farmers to reduce exposure to climate risks (e.g., tighten threshold for coverage, require farmer contributions to disaster fund, limit payments for repeated losses).
  —Consider eliminating either disaster payments or crop insurance so the programs do not undercut each other.
- **Enhance the agricultural technology base**
  —Encourage the development and wider use of information technologies and computer-supported farm-management tools.

32 J. van Schilfgaarde, Associate: Deputy Administrator, Agricultural Research Service, U.S. Department of Agriculture, personal communication, July 1993.

CHAPTER 6 REFERENCES

1. Acock, B., ''Effects of Carbon Dioxide on Photosynthesis, Plant Growth and Other Processes, " in: *Impact of Carbon Dioxide, Trace Gases, and Climate Change on Global Agriculture: Proceedings of a Symposium,* Special Publication 53 (Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, 1990), pp. 45-60.
2. Acock, B., and M.C. Acock, "Modeling Approaches for Predicting Crop Ecosystem Responses to Climate Change, " discussion paper, USDA-ARS Systems Research Laboratory, Beltsville, MD, 1990.
3. Adams, R., J.D. Glyer, and B. McCarl, "The Economic Effects of Climate Change on U.S. Agriculture: A Preliminary Assessment, '' in: *The Potential Effects of Global* Climate *Change on the United Stares,* Appendix C, Volume 1, J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1989), pp. 4-1 to 4-56.
4. Adams, R., et al., "Global Climate Change and U.S. Agriculture, " *Nature, vol. 345, No. 6272,* May 1990, pp. 219-234.
5. Allen, L.H., Jr., ''Plant Responses to Rising Carbon Dioxide and Potential Interaction with Air Pollutants, ' *Journal of Environmental Quality,* vol. 19, 1989, pp. 15-34.
6. Bazzaz, F.A., and E.D. Fajer, "Plant Life in a CO_2-Rich World," *Scientific American,* vol. 266, No. 1, January 1992, pp. 68-74.
7. Biasing, T. J., and A. Solomon, *Response of the North American Corn Belt* to *Climatic Warming,* Publication 2134, Environmental Sciences Division (Oak Ridge, TN: Oak Ridge National Laboratory, 1982).
8. Bockstadter, T. L., et rd., Irrigation Management Component of the Agricultural Energy Conservation Project: Final Report (Lincoln, NE: University of Nebraska Cooperative Extension, 1989).
9. Boggess, W. G., K.A. Anaman, and G.D. Hanson, ''Importance, Causes and Management Responses to Farm Risks: Evidence from Florida and Alabama,' *Southern Journal of Agricultural Economics, vol.* 17, No. *2, 1985,* pp. 105-116.
10. Bonnen, J. T., "A Century of Science in Agriculture: Lessons for Science Policy, " in: *Policy for Agricultural Research,* V.W. Ruttan and C.E. Pray (eds.) (Boulder CO: Westview Press, 1987), pp. 105-137.
11. Bowes, M. D., and P. Crosson, "Consequences of Climate Change for the MINK Economy: Impacts and Responses, " *Climatic Change (in* press).
12. Changnon, S. A., "The 1988 Drought, Barges, and Diversion " *Bulletin of the American Meteorological Society,* vol. 70, 1989, pp. 1092-1104.
13. Chite, R. M., Library of Congress, Congressional Research Service, "Crop Insurance Reform: A Review of the Commission Recommendations," 89-624 ENR, November 1989.
14. Chite, R. M., Library of Congress, Congressional Research Service, ' 'Federal Crop Insurance: Current Issues and Options for Reform,'' 92-318 ENR, March 1992.
15. Chite, R. M., Library of Congress, Congressional Research Service, "Agricultural Disaster Assistance," IB91099, July 1992.
16. Cooper, C.F., "Sensitivities of Western U.S. Ecosystems to Climate Change, " contractor report prepared for the Office of Technology Assessment, August 1992.
17. Council for Agricultural Science and Technology (CAST), *Effective Use of Water in Irrigated Agriculture,* Report 113 (Ames, IA CAST, 1988).
18. Council for Agricultural Science and Technology (CAST), *Preparing U.S. Agriculture for Global Climate Change,* Report 119 (Ames, IA: CAST, 1992).
19. Cox, T.S., J.P. Murphy, and D.M. Rogers, 'Changes in Genetic Diversity in the Red Winter Wheat Regions of the United States, ' *Proceedings of the National Academy of Sciences,* vol. 83, 1986, pp. 5583-5586.
20. Crosson, P.R., "Climate Change and Mid-Latitudes Agriculture: Perspectives on Consequences and Policy Responses,' *Climatic Change, Special* Issue on Greenhouse Gas Emissions: Environmental and Policy Responses, M. Oppenheimer (guest cd.), vol. 15, No. 1/2, 1989, pp. 51-74.
21. Dalrymple, D. G., "Changes in Wheat Varieties and Yields in the United States, 1919- 1984," *Agricultural History,* vol. 62, 1988, pp. 20-36.
22. Dinar, A., and D. Zilberman (eds.), *The Economics and Management of Water and Drainage in Agriculture* (Boston, MA: Kluwer Academic Publishers, 1991).
23. Dudek, D,J., Environmental Defense Fund, New York, NY, ''Economic Implications of Climate Change Impacts on Southern Agriculture, ' paper presented at the Symposium on Climate Change in the Southern United States: Future Impacts and Present Policy Issues, New Orleans, LA, May 1987.
24. Duncan, M.R., "U.S. Agriculture: Hard Realities and New Opportunities, " *Economic Review: Federal Reserve Bank of Kansas City,* February 1989, pp. 3-20.
25. Duvick, D.N., "Plant Breeding in the 21st Century," *Choices,* vol. *7, No. 4, 1992, pp. 26-29.*
26. Easterling, W.E., ''Farm Level Adjustments by Illinois Corn Producers to climatic Change," in: *The Potential Effects of Global Climate Change on the United States,* Appendix C, Volume 2, J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1989).
27. Easterling, W.E., ''Adapting United States Agriculture to climate Change, " contractor report prepared for the Office of Technology Assessment, January 1993.
28. Ek, C. W., Library of Congress, Congressional Research Service, ''Decoupling Farm Programs,' 88-604 ENR, September 1988.
29. Ek, C.W., Library of Congress, Congressional Research Service, "Normal Crop Acreage, " 89-467 ENR, August 1989.
30. Elliot, L.F., and R.E. Wildung, "What Biotechnology *Means* for Soil and Water Conservation" *Journal of Soil and Water Conservation,* January-February 1992, pp. 17-20.
31. Esenwein, G. A., Library of Congress, Congressional Research Service, "Income Tax Averaging: Background and Analysis, " 88-601 ENR, September 1988.
32 Evenson, R.E., P.E. Waggoner, and V.W. Ruttan, "Economic Benefits from Research: An Example from Agriculture," *Science, vol. 205, 1979,* pp. 1101-1107.

33. Experiment Station Committee on Organization and Policy (ESCOP), "Research Agenda for the 1990s: A Strategic Plan for the State Agricultural Experiment Stations and the Cooperative State Research Service,' ESCOP 90-1 (College Station, TX: Texas A&M University, 1990).
34. Fornari, H.D., "The Big Change: Cotton to Soybeana," *Agricultural History*, vol. 53, No. 1, 1979, pp. 245-253.
35. Frederick, K.D., *Processes for Identifying Regional Influences of and Responses to Increasing Atmospheric CO_2 and Climate Change-The MINK Project, Report IV: WaterResources,* U.S. Department of Energy Special Report *TR052F* (Springfield, VA: National Technical Information Service, 1991).
36. Gardner, B.L., et rd., "Agricultural Policy and Risk," in: *Risk Management in Agriculture,* PJ. Barry (ed.) (Ames, IA: Iowa State University Press, 1984), pp. 231-261.
37. Glantz, MM., and J.H. Ausubel, "Impact Assessment by Analogy: Comparing the Impacts of the Ogallala Aquifer Depletion and CO_2-Induced Climate Change," in: *Societal Responses to Regional Climatic Change: Forecasting by Analogy,* MH. Glantz (cd.) (Boulder, CO: Westview Press, 1988).
38. Hahn, G.L., "Housing for Cattle, Sheep and Poultry in the Tropics," in: *Animal Production in the Tropics,* MK. Yousef (ed.) (New York, NY: Praeger, 1985), pp. 43-72.
39. Hahn, G.L., P. Klinedienst, and D.A. Wilhite, "ClimateChange Impacts on Livestock Production and Management" paper presented at the 1992 International Summer Meeting of the American Society of Agricultural Engineers, St. Joseph, MI, 1992.
40. Hanson, J.D., and B.B. Baker, *The Potential Effect of Global Climate Change on Rangeland Livestock Production for the United States (Fort* Collins, CO: USDA Agricultural Research Service, 1992).
41. Hart, J.F., "Change in the Corn Belt," *The Geographical Review,* vol. *76, No* .1, 1986, pp. 51-72.
42, Heid, W, G., U.S. *Wheat Industry,* Agricultural Economic Report No. 432 (Washington DC: U.S. Department of Agriculture, 1979).
43. High Plains Associates, *Congressional Briefing on the Six-State High Plains-Ogallala Aquifer Regional Resources Study* (Austin, TX: Camp, Dresser and McKee, Inc., 1982).
44. High Plains Underground Waler Conservation District No. 1, *Our Fourth Decade of Service, 1981 -1991* (Lubbock, TX: High Plains Underground Water Conservation District No. 1, 1991).
45. Howe, C.W., J.K. Lam, and K.R.Weber, ''The Economic Impacts of Agriculture-to-Urban Water Transfers on the Area of Origin: A Case Study of the Arkansas River Valley in Colorado,' *American Journal of Agricultural Economics,* vol. *72, No. 5,* December 1990, pp. 120&1204.
46. Kane, S., J. Reilly, and J. Tobey, "An Empirical Study of the Economic Effects of Climate Change on World Agriculture," *Climatic Change,* vol. 21, No. 1, 1992, pp. 17-36.
47. Karl, T.R., R.R. Heim, and R.G. Quayle, "The Greenhouse Effect in Central North America: If Not Now, When?" *Science,* vol. 251, No. 4997, 1991, pp. 1058-1061.
48. Keller, L.F., G.H. Craig, and J.W. Weber, "Managing Crisis: The Effectiveness of Local Districts for Control of Ground Water Mining," *Water Resources Bulletin,* vol. 17, No. 4, 1981, pp. 647-654.
49, Kimball, B.A., N.J. Rosenberg, and L.H. Allen, Jr., *Impact of Carbon Dioxide, Trace Gases and Climate Change on Global Agriculture, Special* Publication No. 53 (Madison, WI: American Society of Agronomy, 1990).
50. Klinedienst, PL., et al., ''The Potential Effects of Climate Change on Summer Season Dairy Milk Production and Reproduction,'' *Climatic Change,* vol. 23, No. 1, January 1993, pp. 21-36.
51. Kromm, D.E., and S.E. White, ''Variability in Adjustment Preferences to Groundwaves Depletion in the American High Plains, " *Water Resources Bulletin, vol. 22, No. 5, 1986,* pp. 791-801.
52. Lawlor, D.W., and R.A.C. Mitchell, "The Effects of Increasing CO_2 on Crop Photosynthesis and Productivity: A Review of Field Studies," *Plant, Cell and Environment,* vol. *14,* 1991, pp. 807-818.
53. Lehe, J.M., "The Effects of Depletion of the Ogallala Aquifer and Accompanying Impact on Economic and Agricultural Production in the Southern High Plains Region of the United States, " in: *Proceedings of the Association of Ground Water Scientists and Engineers, Southern Regional Ground Water Conference* (Worthington, OH: National Water Well Association, 1986), pp. 410-426.
54. Lewandrowski, J., and R. Brazee, "GOVernment Farm Programs and Climate Change: A First Look," in: *Economic Issues in Global Climate Change: Agriculture, Forestry, and Natural Resources,* J. Reilly and M. Anderson (eds.) (Boulder, CO: Westview Press, 1992), pp. 132-147.
55. Loomis, R. S., *Crop Ecology: Productivity and Management in Agricultural Systems (New* York, NY: Cambridge University Press, 1992).
56. Major, D.J., et al., ''Agronomy of Dryland Corn Production at the NorthernFringe of the Great Plains,' *Journal of Production Agriculture,* vol. *4, No, 4,* 1991, pp. 606-613.
57. Martinez, D., "Wanted: Policies to Cope with Differences in Farming Regions," *Farmline,* vol. *8, No.* 11, 1987, pp. 11-13.
58. McLaughlin, S.P., "Economic Prospects for New Crops in the SouthwesternUnited States,' *Economic Botany,* vol. *39, No,* 4, 1985, pp. 473-481.
59. Mearns, L., "Implications of Global Warming Climate Variability and the Occurrence of Extreme Climate Events,' in: *Drought* Assessment, *Management, and Planning: Theory and Case Studies,* D. Wilhite (ed.) (Boston, MA: Kluwer Academic Publishers, 1993).
60. Michaels, P.J., "Economic and Climatic Factors in Acreage Abandonment Over Marginal Cropland," *Climatic Change,* vol. *7, 1985, pp. 185-202.*
61. Miller, K.A., "Public and Private Sector Responses to Florida Cirrus Freezes,'' in: *Societal Responses* to *Regional Climatic Change: Forecasting by Analogy,* M.H. Giant.z (cd.) (Boulder, CO: Westview Press, 1988).

62. Murdock, S.H., and D.E. Albrecht, Department of Rural Sociology, Texas A&M University, "The Impacts of Technology on the Industrialization of Agriculture and on Rural Areas: Implication for the Future of Rural America," paper presented at the annual meeting of the American Association for the Advancement of Science, Chicago, IL, 1992.
63. National Research Council, *Agricultural Biotechnology: Strategies for National Competitiveness* (Washington, *DC:* National Academy Press, 1987).
64. National Research Council, *Water Transfers in the West: Efficiency, Equity, and the Environment* (Washington DC: National Academy Press, 1992).
65. National Research Council, National Academy of Sciences, *Policy Implications of Greenhouse Warming,* Report of the Committee on Science, Engineering and Public Policy (Washington, DC: National Academy Press, 1991).
66. Nellis, M.D., "Land-Use Adjustments to Aquifer Depletion in Western Kansas, " in: *Demands on Rural Lund: Planning for Resource Use, C.* Cocklin, B. Smit, and T. Johnston (eds.) (Boulder, CO: Westview Press, 1987), pp. 71-84.
67. Obmascik, M., and P. O'Driscoll, "Colorado Water: The New Harvest," *The Denver Post,* July 19-22, 1992.
68. Parry, M.L., T.R. Carter, and N.T. Konijin (eds.), *The Impact of Climatic Variations on Agriculture* (Dordrecht, Germany: Kluwer, 1988).
69. Peterson, D.F., and A.A. Keller, "Irrigation" in: *Climate Change and U.S. Water Resources,* P.E. Waggoner (cd.) (New York, NY: John Wiley and Sons, 1990), pp. 269-306.
70. Porter, J.H., M.L. Parry, and T.R. Carter, "The Potential Effects of Climatic Change on Agricultural Insect Pests, ' *Agricultural and Forest Meteorology,* vol. *57,* 1991, pp. 221-240.
71. Probst, A.H., and R.W. Judd, "Origin, U.S. History and Development and World Distribution' in: *Soybeans: Improvement, Production and Uses,* B.E. Caldwell (cd.), Agronomy Series 16 (Madison, WI: American Agronomy Society, 1979), pp. 1-16.
72. Rawson, J. M., Library of Congress, Congressional Research Service, "New Crops and New Farm Products: A Briefing," 88-771 ENR, December 1988.
73. Rawson, J. M., Library of Congress, Congressional Research Service, "Agricultural Research and Extension: Current Issues," 93-83 ENR, January 1993.
74. Reisner, M., and S. Bates, *Overtapped Oasis: Reform or Revolution for Western Water (Washington DC:* Island Press, 1990).
75. Ritchie, J.T., B.D. Baer, and T.Y. Chou, "Effect of Global Climate Change on Agriculture in the Great Lakes Region," in: *The Potential Effects of Global Climate Change on the United States,* Appendix C, Volume 1, J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1989), pp. 1-1 to 1-30.
76. Rosenberg, N.J., "The Increasing CO_2 Concentration in the Atmosphere and its Implication on Agricultural productivity, Part II: Effects Through CO_2-Induced climatic Change, " *Climatic Change, vol. 4, 1982,* pp. 239-254.
77. Rosenberg, N.J., "Climate, Technology, Climate Change and Policy: The Long Run," in: *The Future of the North American Granary: Politics, Economics and Resource Constraints in North American Agriculture,* C.F. Runge (ed.) (Ames, IA: Iowa State University Press, 1986), pp. 93-127.
78. Rosenberg, N.J., "Adaptation of Agriculture to Climate Change," *Climatic Change,* vol. 21, No. 4, 1992, pp. 385405.
79. Rosenberg, NJ., and P.R. Crosson, "The MINK Project: A New Methodology for Identifying Regional Influences of, and Responses to, Increasing Atmospheric CO_2 and Climate Change, " *Environmental Conservation, vol.* 18, No. *4,* 1991, pp. 313-322.
80. Rosenzweig, C., "Potential Effects of Climate Change on Agricultural Production in the Great Plains: A Simulation Study, ' in *The Potential Effects of Global Climate Change on the United States,* Appendix C, Volume 1, J. Smith and D. Tirpak (eds.) (Washington, DC: U.S. Environmental Protection Agency, 1989), pp. 3-1 to 3-43.
81. Rosenzweig, C., and M. Parry, *Climate Change and World Food Supply* (Oxford, England: University of Oxford, in press).
82. Ruttan, V. W., *Agricultural Research Policy* (Minneapolis, MN: University of Minnesota Press, 1982).
83. Ruttan, V.W., "Biological and Technical Constraints on Crop and Animal Productivity: Report of a Dialogue, " Staff Paper P89-45 (St. Paul, MN: Department of Agricultural and Applied Economics, University of Minnesota, 1989).
84. Ruttan, V. W., "W. Parry: *Climate Change and World Agriculture," Environment, vol. 33,* 1991, pp. 25-29 (book review).
85. Ruttan, V.W., "Constraints on Sustainable Growth in Agricultural Production: Into the 21st Century, " *Outlook on Agriculture, vol. 20, No. 4,* 1991, pp. 225-234.
86. Savdie, I., et al., "Potential for Winter Wheat Production in Western Canada: A CERES Model Winterkill Risk Assessmerit, ' *Canadian Journal of Plant Science,* vol. *71,* No. 1, 1991, pp. 21-30.
87. Smith, J., and D. Tirpak (eds.), *The Potential Effects of Global Climate Change on the United States (Washington DC:* U.S. Environmental Protection Agency, 1989).
88. Solley, W.B., R.R. Pierce, and H.A. Perlman, "Estimated Use of Water in the United States in 1990, " U.S. Geological Survey Circular 1081 (Denver, CO: U.S. Geological Survey, 1993).
89. Sonka, S. T., "Adaptation and Adjustments in Drought-Prone Areas: Research Directions, " in: *Planning for Drought: Toward a Reduction of Societal Vulnerability,* D.A. Wilhite and W.E. Easterling (eds.) (Boulder, CO: Westview Press, 1987), pp. 351-368.
90. Sonka, S. T., and G.F. Patrick, "Risk Management and Decision Making in Agricultural Firms," in: *Risk Management in Agriculture,* Peter J. Barry (cd.) (Ames, IA: Iowa State University Press, 1984).
91. Stam, J.M., et al., *Farm Financial Stress, Farm Exits, and Public Sector Assistance to the Farm Sector in the 2980s,* Agricultural Economic Report No. 645 (Washington, DC: Economic Research Service, U.S. Department of Agriculture, 1991).
92. Stepelton, B. M., "Texas Groundwater Legislation: Conservation of Groundwater or Drought by process, ' *Natural Resources Journal,* vol. *26, No. 4, 1986,* pp. 871-881.

93. Stewart, J.I., ''Managing Climatic Risk in Agriculture,'' in: *Risk in Agriculture: Proceedings of the Tenth Agriculture Sector Symposium,* D. Holden, P. Hazell, and A. Pritchard (eds.) (Washington, DC: World Bank, 1991), pp. 17-38.

94. Unger, P.W., and B.A. Stewart, "Soil Management for Efficient Water Use: An Overview," *Limitations to Efficient Water Use in Crop Production* (Madison, *WI: American* Society of Agronomy, 1983),

95. U.S. Congress, Congressional Budget Office, ''The Outlook for Farm Commodity Programs Spending, Fiscal Years 1991-1996," June 1991.

%. U.S. Congress, General Accounting Office, *Crop Insurance Program Has* Not *Fostered Significant Risk Sharing by Insurance Companies,* GAO/RCED-92-25 (Gaithersburg, MD: Us. General Accounting office, 1992).

97. U.S. Congress, Office of Technology Assessment, *Water Related Technologies,* OTA-F-212 (Springfield, VA: National Technical Information Service, October 1983).

98. U.S. Congress, Office of Technology Assessment, *Enhancing the Quality of U.S. Grain for International Trade,* OTA-F-399 (Washington DC: U.S. Government Printing Office, February 1989),

99. U.S. Congress, Office of Technology Assessment, *Agricultural Research and Technology Transfer Policies for the 1990s,* OTA-F-448 (Washington DC: U.S. Government printing Office, March 1990).

100. U.S. Congress, Office of Technology Assessment, *Beneath the Bottom Line: Agricultural Approaches to Reduce Agrichemical Contamination of Groundwater,* OTA-F-418 (Washington, *DC:* U.S. Government Printing Office, November 1990).

101. U.S. Congress, Office of Technology Assessment, *Rural America at the Crossroads Networking for the Future,* OTA-TCT-471 (Washington, DC: U.S. Government Printing Office, April 1991).

102. U.S. Congress, Office of Technology Assessment, *Agricultural Commodities as Industrial Raw Materials,* OTA-F-*476* (Washington, DC: U.S. Government Printing Office, June 1991).

103, U.S. Congress, Office of Technology Assessment, *A New Technological Era for American Agriculture,* OTA-F-474 *(Washington DC:* U.S. Government Printing office, August 1992).

104. U.S. Department of Agriculture, *Agricultural Statistics* (Washington, DC: Us. Government Printing office, 1992).

105. U. S. Department of Agriculture, Agricultural Stabilization and Conservation Service, Commodity *Credit Corporation Report of Financial Conditions and Operations, 1992.*

106. U.S. Department of Agriculture, Economic Research Service, *Economic Indicators of the Farm Sector: Farm Sector Review,* 1991.

107. U.S. Department of Agriculture, Economic Research Service, *Agricultural Irrigation and Water Use, Agriculture* Information Bulletin 638, 1992.

108. U.S. Department of Agriculture, Economic Research Service, *Agricultural Resources: Cropland, Water, and Conservation Situation and Outlook, AR-27,* 1992.

109. U.S. Department of Agriculture, Foreign Agricultural Service, *Foreign Agricultural Commodity Circular Series, 1992.*

110. U, S. Department of Agriculture, National Agricultural Statistical Service, *Crop Production, 1991.*

111. U.S. Department of Agriculture, Soil Conservation Service, *Summary Report, 1987 National Resources Inventory,* Statistical Bulletin No. 790, 1989.

112. U.S. Department of Agriculture, Soil Conservation Service, *The Second RCA Appraisal: Soil, Water, and Related Resources on Nonfederal Land in the United States—Analysis of Conditions and Trends,* Miscellaneous Publication No. 1482 (Washington, DC: U.S. Department of Agriculture, June 1989, slightly revised May 1990).

113. U, S. Department of Commerce, Bureau of Economic Analysis, *Survey of Current Business,* January 1992.

114. U.S. Department of Commerce, Bureau of the Census, *Current Population Reports, Series* p25, 1993.

115, Wahl, R,W., *Markets for Federal Water: Subsidies, Property Rights, and the Bureau of Reclamation (Washington* DC: Resources for the Future, 1989).

116. White, D., D. Collins, and M. Howden, ''Drought in Australia: Prediction, Monitoring, Management, and Policy," in: *DroughtAssessment, Management, and Planning: Theory and Case Studies* (Boston, MA: Kluwer Academic Publishers, 1993).

117. Wilhite, D.A., "The Ogallala Aquifer and Carbon Dioxide: Are Policy Responses Applicable?" in: *Societal Responses to Regional Climate Change: Forecasting by Analogy,* M.H. Glantz *(cd.)* (Boulder, CO: Westview Press, 1988), pp. 353-374.

118. Wyatt, A.W., "Water Management-southern High Plains of Texas,'' in: *Proceedings of the Natural Resources Law Center's Twelfth Annual Summer Program, Innovations in Western Water Law and Management* (Boulder, CO: University of Colorado School of Law, 1991).

119. Zinn, J., Library of Congress, Congressional Research Service, "Subsidies for Irrigated Agricultural Lands in the Arid West-an Overview," 85-594 ENR, February 1985.

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Appendix B: Acknowledgments

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