environment

Coping with Global climate change

The Role of Adaptation in the United States

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Contents

Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

Throughout the next century and beyond, global climate change will have significant effects on both important economic sectors and natural resources across the United States. Global temperatures are projected to increase 2.5-10.4ºF by 2100, and at least some of this warming is now unavoidable. Although the natural streams, wetlands, and biodiversity of the United States have a limited capacity to adapt to a changing climate, those systems that are managed by humans, such as agriculture, water resources, and coastal development can be handled in ways to reduce the severity of adverse impacts.

Adaptation and Global Climate Change discusses how the United States might cope with anticipated climate change impacts in the coming decades. This report provides a review of the role of adaptation in addressing climate change, the options available for increasing our ability to adapt, and the extent to which adaptation can reduce the consequences of climate change to the U.S. economy and natural resources. Report authors Bill Easterling, Brian Hurd, and Joel Smith find:

- ***Adaptation is an important complement to greenhouse gas mitigation policies.*** Reducing greenhouse gas emissions is the only effective mechanism for preventing adverse impacts of climate change. However, given that additional future climate change is now inevitable regardless of mitigation efforts, adaptation is an essential strategy for reducing the severity and cost of climate change impacts.

- ***Adapting to climate change will not be a smooth or cost-free endeavor.*** Although the United States has diverse options and resources for adapting to the adverse effects of climate change, changes will be made in an atmosphere of uncertainty. Substantial investments and adjustments will need to be made even with imperfect information or foresight, and successful adaptation will become even more challenging with more rapid rates or greater degrees of warming.

- ***Managed systems will fare better than natural systems and some regions will face greater obstacles than others.*** Even if there are some successes in adapting to climate change at the national level, there will still be regional and sectoral losers. In particular, there is limited ability for humans to improve the adaptive capacity of natural ecosystems, which are not as easily managed and which face degradation from multiple stresses.

- ***Proactive approaches to adaptation are more likely to avoid or reduce damages than reactive responses.*** Anticipatory planning among government institutions and important economic sectors will enhance resilience to the effects of climate change. Government at all levels should consider the implications of climate change when making investments in long-lived infrastructure.

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Executive Summary

Climate change resulting from increased greenhouse gas concentrations has the potential to harm societies and ecosystems. In particular, agriculture, forestry, water resources, human health, coastal settlements, and natural ecosystems will need to adapt to a changing climate or face diminished functions. Reductions in emissions of greenhouse gases and their concentration in the atmosphere will tend to reduce the degree and likelihood that significantly adverse conditions will result. Consideration of actions—e.g., mitigation policy—that can reduce this likelihood is reasonable and prudent, and has generally been the primary focus of public attention and policy efforts on climate change. However, recognition is increasing that the combination of continued increases in emissions and the inertia of the climate system means that some degree of climate change is inevitable. Even if extreme measures could be instantly taken to curtail global emissions, the momentum of the earth's climate is such that warming cannot be completely avoided. Although essential for limiting the extent, and indeed the probability, of rapid and severe climate change, mitigation is not, and this paper argues, should not be, the only protective action in society's arsenal of responses.

Adaptation actions and strategies present a complementary approach to mitigation. While mitigation can be viewed as reducing the likelihood of adverse conditions, adaptation can be viewed as reducing the severity of many impacts if adverse conditions prevail. That is, adaptation reduces the level of damages that might have otherwise occurred. However, adaptation is a risk-management strategy that is not free of cost nor foolproof, and the worthiness of any specific actions must therefore carefully weigh the expected value of the avoided damages against the real costs of implementing the adaptation strategy.

Adaptation to environmental change is a fundamental human trait and is not a new concept. Throughout the ages, human societies have shown a strong capacity for adapting to different climates and environmental changes, although not always successfully. As evidenced by the widespread and climatically diverse location of human settlements throughout the world, humans have learned how to thrive in a wide variety of climate regimes, ranging from cold to hot and from humid to dry. The resilience and flexibility exhibited in the patterns of human settlements evidence an inherent desire and some measure of capacity to adapt.

For human systems, the success of adaptation depends critically on the availability of necessary resources, not only financial and natural resources, but also knowledge, technical capability, and institutional resources. The types and levels of required resources, in turn, depend fundamentally on the nature and abruptness of the actual or anticipated environmental change and the range of considered responses.

The processes of adaptation to climate change in both human and natural systems are highly complex and dynamic, often entailing many feedbacks and dependencies on existing local and temporal conditions. The uncertainties introduced by the complexity, scale, and limited experience with respect to anthropogenic climate change explain the limited level of applied research conducted thus far on adaptation, the reliance on mechanistic assumptions, and the widespread use of scenarios and historical analogues. In addition, many social, economic, technological and environmental trends will critically shape the future ability of societal systems to adapt to climate change. While such factors as increased population and wealth will likely increase the potential level of material assets that are exposed to the risks of climate change, greater wealth and improved technology also extend the resources and perhaps the capabilities to adapt to climate change. These trends must be taken into account when evaluating the nature and scale of future adaptive responses and the likelihood that they will succeed.

The implications of climate change are more dire for natural systems, because it will be difficult for many species to change behavior or migrate in response to climate change. While biological systems might accommodate minor (or slowly occurring) perturbations in a smooth continuous fashion, even minor changes in climate may be disruptive for many ecosystems and individual species. In addition, many of the world's species are currently stressed by a variety of factors including urban development, pollution, invasive species, and fractured (or isolated) habitats. Such conditions, coupled with the relatively rapid rate of anticipated climate change, are likely to challenge many species' resiliency and chances for successful adaptation.

Key insights and findings on adaptation and its potential for success are summarized below:

1) Adaptation and mitigation are necessary and complementary for a comprehensive and coordinated strategy that addresses the problem of global climate change. By lessening the severity of possible damages, adaptation is a key defensive measure. Adaptation is particularly important given the mounting evidence that some degree of climate change is inevitable. Recognizing a role for adaptation does not, however, diminish or detract from the importance of mitigation in reducing the rate and likelihood of significant climate change.

2) The literature indicates that U.S. society can on the whole adapt with either net gains or some costs if warming occurs at the lower end of the projected range of magnitude, assuming no change in climate variability and generally making optimistic assumptions about adaptation. However, with a much larger magnitude of warming, even making relatively optimistic assumptions about adaptation, many sectors would experience net losses and higher costs. The thresholds in terms of magnitudes or rates of change (including possible non-linear responses) in climate that will pose difficulty for adaptation are uncertain. In addition, it is uncertain how much of an increase in frequency, intensity, or persistence of extreme weather events the United States can tolerate.

3) To say that society as a whole "can adapt" does not mean that regions and peoples will not suffer losses. For example, while the agricultural sector as a whole may successfully adapt, some regions may gain and others may lose. Agriculture in many northern regions is expected to adapt to climate change by taking advantage of changing climatic conditions to expand production, but agriculture in many southern regions is expected to contract with warmer, drier temperatures. Individual farmers not benefiting from adaptation may lose their livelihoods. In addition, other individuals or populations in these and other regions can be at risk, because they could be adversely affected by climate change and lack the capacity to adapt. This is particularly true of relatively low-income individuals and groups whose livelihoods are dependent on resources at risk from climate change.

4) Adaptation is not likely to be a smooth process or free of costs. While studies and history show that society can on the whole adapt to a moderate amount of warming, it is reasonable to expect that mistakes will be made and costs will be incurred along the way. People are neither so foolish as to continue doing what they have always done in the face of climate change, nor so omniscient as to perfectly understand what will need to be done and to carry it out most efficiently. In reality, we are more likely to muddle through, taking adaptive actions as necessary, but often not doing what may be needed for optimal or ideal adaptation. Additionally, adaptation is an on-going process rather than a one-shot instantaneous occurrence. Compounding society's shortcomings, a more rapid, variable, or generally unpredictable climate change would add further challenges to adaptation.

5) Effects on ecosystems, and on species diversity in particular, are expected to be negative at all but perhaps the lowest magnitudes of climate change because of the limited ability of natural systems to adapt. Although biological systems have an inherent capacity to adapt to changes in environmental conditions, given the rapid rate of projected climate change, adaptive capacity is likely to be exceeded for many species. Furthermore, the ability of ecosystems to adapt to climate change is severely limited by the effects of urbanization, barriers to migration paths, and fragmentation of ecosystems, all of which have already critically stressed ecosystems independent of climate change itself.

6) Institutional design and structure can heighten or diminish society's exposure to climate risks. Long-standing institutions, such as disaster relief payments and insurance programs, affect adaptive capacity. Coastal zoning, land-use planning, and building codes are all examples of institutions that can contribute to (or detract from) the capacity to withstand climate changes in efficient and effective ways.

7) Proactive adaptation can reduce U.S. vulnerability to climate change. Proactive adaptation can improve capacities to cope with climate change by taking climate change into account in long-term decision-making, removing disincentives for changing behavior in response to climate change (such as removing subsidies for maladaptive activities), and introducing incentives to modify behavior in response to climate change (such as the use of market-based mechanisms to promote adaptive responses). Furthermore, improving and strengthening human capital through education, outreach, and extension services improves decision-making capacity at every level and increases the collective capacity to adapt.

I. Introduction

A. Climate Change, Impacts, and Adaptation

Evidence is accumulating that the Earth's climate is undergoing change, and observations are consistent with scientific expectations concerning the increasing concentrations of greenhouse gases in the atmosphere. Global temperatures have already increased by approximately 0.6°C (1°F) over the last century, and the Intergovernmental Panel on Climate Change (IPCC) concluded that the majority of warming over the past 50 years is likely the result of human activities (Houghton et al., 2001). In addition, the IPCC projects that average global temperatures will increase by 1.4 to 5.8°C (2.5 to 10.4°F) this century. Warming in the United States is anticipated to be approximately one-third greater than the global average (Wigley, 1999). This increase in global temperature will be accompanied by a rising sea level, an accelerated hydrologic cycle resulting in greater precipitation, and a potential increase in climate variability, such as extremes of temperature, precipitation, and storm activity.

The potential impacts of climate change are the subject of many studies and investigations (e.g., McCarthy et al., 2001). Studies generally agree that, for better or worse, several critical sectors of the U.S. economy and other aspects of human welfare will be affected by climate change. The effects on specific sectors of the economy and natural resources are the subject of the Environmental Impacts series produced by the Pew Center on Global Climate Change (see Table 1). Each of these reports highlights the potential implications of climate change to various sectors and discusses how adaptations can ameliorate the severity of possible climate change impacts or, in some cases, prevent adverse impacts altogether.

A critical component of understanding how societal systems will be affected by climate change is understanding how these systems will or can adapt to the changes. Adaptation to social and environmental change is a fundamental human trait. Humans have always been able to adapt to environmental changes. Some of the physical features that distinguish fully modern humans from their ancestors were evolutionary adaptations to climatic changes occurring in eastern Africa during the Miocene global cooling

(Vrba, 1992; Bromage and Schrenk, 1995). For example, as grasslands emerged out of closed canopy forests, natural selection favored species that could walk on two legs, a stance better adapted to this new open ground. The larger brain sizes of fully modern humans subsequently terminated further physiological evolution in favor of behavioral adaptations to environmental change. Humans out-thought environmental challenges rather than physically changing. Adaptation most likely began by migration to places of new opportunity and modification of diet to accommodate a changing food endowment. Adaptation to the climate changes that lie ahead could be one of the next great challenges to human ingenuity.

The processes of adaptation in both human and natural systems are highly complex and dynamic, often entailing many feedbacks and dependencies on existing local and temporal conditions. The complexity, scale and limited experience with respect to anthropogenic climate change explain the limited level of applied research conducted thus far on adaptation, the reliance on mechanistic assumptions, and the widespread appeal of scenarios and historical analogies.

Adaptation actions and strategies present a complementary approach to those of greenhouse gas mitigation. Efforts that limit or reduce climate-driving forces (i.e., mitigation or reduction of greenhouse gas emissions) tend to reduce the degree and likelihood that significantly adverse conditions will result. Actions that can reduce this likelihood are thus reasonable and prudent, and to a large measure have been the primary focus of public attention and policy efforts on climate change. However, recognition that the climate system has a great deal of inertia is increasing, and that mitigation efforts alone are insufficient to protect the Earth from some degree of climate change. Even if extreme measures could be taken instantly to curtail global emissions, the momentum of the Earth's climate is such that additional warming would still happen. Although essential for limiting the extent of rapid and severe climate change, mitigation is not —and this report argues, should not be—the only protective action in society's arsenal of responses.

This report explains the concepts of vulnerability and adaptation in the context of climate change. It illustrates selected successes and failures of reactive adaptation to analogous changes in environmental or socioeconomic conditions, and it explores the challenges and potential benefits of deliberately stoking the nation's adaptive capacity with proactive policies in anticipation of climate change.

Table 1

Pew Center Environmental Impact Reports and Key Fidings

Sector	Authors	Impacts
Agriculture	Adams et al., 1999	• High sensitivity, but high adaptive capacity • National output estimated to peak at 2-3°C (4-5°F) increase; output falls at greater than 5°C increase • Southern areas more likely to face reduced output of grain production
Freshwater resources	Frederick and Gleick, 1999	• High sensitivity, but high adaptive capacity, although many impediments • More floods and droughts; earlier snowmelts • Southwest is most sensitive
Sea-level rise	Neumann et al., 2000	• Cost of adapting to 0.5-meter sea-level rise estimated at $20 to $138 billion • Southeast and mid-Atlantic coasts most vulnerable
Terrestrial ecosystems	Malcolm and Pitelka, 2000	• High sensitivity and vulnerability • Substantial change in distribution of species; reduction in biodiversity expected • Productivity increase with a few degrees of warming; decline expected at higher temperatures and CO_2 concentrations
Forestry	Shugart et al., 2003	• Substantial changes in location and productivity of forests • Plantation forests have greatest adaptive capacity • Northern areas may gain productivity; other regions face mixed effects
Human health	Balbus and Wilson, 2000	• Strong public health system should minimize risks • Heat stress expected to increase; difficult to predict infectious disease rates • Risks from natural hazards such as flooding may increase
Freshwater aquatic ecosystems	Poff et al., 2002	• High sensitivity and vulnerability • Substantial change in distribution of species; reduction in biodiversity expected • Warm-water fish may benefit; cool- and cold-water fish face greater harm
Coastal and marine ecosystems	Kennedy et al., 2002 and Buddemeier et al., 2004	• High sensitivity and vulnerability • Estuaries, especially wetland areas, will be significantly affected by changes in temperature and runoff • Loss of wetlands from sea-level rise will reduce ecosystem productivity; more modest effects expected in open ocean ecosystems, although productivity could decline • Coral reefs likely to be harmed by higher temperatures and the effects of increased atmospheric CO_2 on ocean chemistry

Note: Pew Center Environmental Impacts series focuses on implications of climate change for the United States (see also Smith, 2004).

B. Adaptation Concepts and Definitions

To understand the potential for adaptation to ameliorate adverse impacts of climate change or the need to anticipate the impacts of changes in climate, it is first necessary to understand the terms vulnerability, exposure, sensitivity, and adaptive capacity. Vulnerability is a measure of a system's susceptibility to climate change, which is a function of the system's exposure, sensitivity, and adaptive capacity.

Exposure is the degree to which elements of a climate-sensitive system are in contact with climate. For example, the more people move to low-lying coastal areas, the greater is the population's exposure to sea-level rise and increased coastal storms. Sensitivity is the degree to which a system can be affected by climate change without accounting for adaptation. In agriculture for example, corn is far more physiologically sensitive to climate change than wheat is, because corn is more sensitive to hot and dry conditions and is less able to take advantage of higher carbon dioxide (CO_2) levels.

A change in a system's behavior in response to an external stimulus, such as a shock or a change in climate is an adaptation. For example, an increase in precipitation over a grassland ecosystem may enable shrubs and trees to encroach upon grasslands. A rise in peak river flows could increase flooding and lead to adaptation in the form of more substantial management measures to protect against floods, such as higher levees or improved evacuation procedures. How well a system could adjust to realized or even anticipated environmental changes indicates the system's adaptive capacity. Availability and accessibility to adjustment opportunities serve as the foundation for understanding and defining a system's adaptive capacity. In managed systems, wealth, availability of technology, appropriate decision-making capabilities, human capital, social capital, risk spreading (e.g., insurance), ability to manage information, and the perceived attribution of the source of stress (Yohe and Tol, 2002) all contribute significantly to adaptive capacity and the capability of such systems to actively and adequately respond to changing environments. Human systems are further distinguished by their capacity to anticipate environmental changes and respond accordingly so as to best prepare for expected future conditions. This distinction is important in characterizing reactive and proactive adaptations that are discussed later in this report.

The adaptive capacity of natural ecosystems is much more limited. Biological systems have the adaptive capacity to change and evolve in response to a variety of inherent genetic changes and external pressures, including climate. Biological systems are constantly responding to disturbance; however, the time scales necessary for natural selection are generally much longer than a few decades during which the climate could be changed. In such cases, biological systems might accommodate minor (or slowly occurring) perturbations in a smooth continuous fashion, although even minor changes in climate can be disruptive for some ecosystems and species. However, many of the world's ecosystems are stressed by a variety of disturbances, including pollution, invasion of exotic species, and fragmentation (or isolation) of habitats. Such conditions, coupled with the relatively rapid rate of anticipated climate change, will likely erode a system's resiliency and reduce its chances for successful adaptation.

Although the climate change literature contains no standard terminology for adaptation (but see Smit et al., 2001, for an overview), it is important to distinguish between adaptation and resilience—terms that are often inappropriately used interchangeably. This distinction can be made through the identification of two general strategies for adaptation: reactive adaptation and proactive adaptation. Reactive (sometimes referred to as autonomous) adaptation is consistent with the concept of resilience, which systems ecologists (e.g., Holling, 1986) and political ecologists (e.g., Gunderson et al., 1995) define as the degree to which a system can absorb disturbance and still snap back to its pre-disturbance steady state. For example, hurricanes often severely disrupt coastal ecosystems and cause catastrophic property damage. Within a few years, barrier island vegetation may show little evidence of salt-water damage from the hurricane, and subsidized hurricane insurance encourages complete rebuilding of coastal property to pre-hurricane specifications. Such reactive adaptations to climate impacts utilize the existing political, economic, and technological regimes of society or the ability of species to modify behavior or respond to the disturbance. Although reactive adaptations can provide resilience in the short term by restoring the coastal system to its prior condition, vulnerability to further hurricane damage can increase over the long term because continued coastal development increases the system's exposure to climate.

Sometimes trying to return a system to its pre-event condition is not the wisest response, because the historical steady state may be wholly inappropriate for the new (or existing) set of environmental and socioeconomic conditions. In contrast with reactive adaptation, proactive or anticipatory adaptation is consistent with the concept of adaptive reorganization whereby a system survives disturbance by altering existing relationships or establishing new relationships and components (Holling, 1986). Such adaptations move beyond the concept of resilience because they represent a fundamental reorganization of the system (rather than a preservation of the status quo) to improve its capacity to avert future damages. In the context of climate change, this reorganization could involve the development of new economic, technological, and political institutions to avert damages, or it could mean taking advantage of opportunities in anticipation of future climate change. For example, proactive adaptation to reduce the long-term vulnerability of coastal communities to hurricane damage may necessitate changes in building codes, changes in zoning rules for new development, improvements to emergency management and evacuation routes, and changes in location or livelihood (see Burton, 1996, for a list of the many types of adaptation). The extent to which adaptation measures are reactive versus proactive has important implications for the success and cost of adaptation, and the implications of these two approaches for addressing the potential consequences of climate change is a central theme of this report.

The rate of future climate change is another fundamental consideration in the process of adaptation, in part because the implementation of adaptation measures is not an instantaneous occurrence but one that develops over time. The trajectory of future climate change can range anywhere between gradual and smooth to rapid and discontinuous. To the extent that climate change is rapid or discontinuous, adaptation will be more difficult because faster rates of climate change necessitate more rapid and costly adjustments associated with any adaptive response and increase the likelihood that necessary adaptive responses will lag changes in climate.

For the purpose of this report, a successful adaptation is defined as one that follows a climate change causing adverse impacts and maintains a system at approximately the same level of welfare or services as was provided before the change in climate. If the adaptation can completely offset the loss from climate change, it is successful. Although less straightforward, adaptation also should be considered successful if it maintains services or welfare with a small or minimal loss. For example, adaptation is still successful if it offsets most agricultural income loss, but leaves an individual farmer with a small loss. The farmer may be forced to lower profit expectations, but the farmer remains solvent and flexible enough to be able to develop new production and marketing strategies for the future.

C. Changes in Human Adaptive Capacity

When considering the ability of adaptation to reduce societal system vulnerability, it is important to note that life in America in 2050 or 2100 is likely to be quite different from life today, independent of climate change. Some changes will simply involve the gradual evolution of present trends; others will be surprises. These changes will fundamentally alter the sociopolitical, technological, economic, and cultural landscapes in which climate change occurs—they will set the backdrop of adaptation. Borrowing from an approach used by Schelling (National Research Council, 1983), a sampling of some of the remarkable changes that reshaped American life over the past 40 years helps frame the importance of anticipating future change:

- In 1960, the world's largest computers had 8,000 bytes of memory and occupied entire rooms—today's personal computers have 4,000 times as much memory in a small fraction of the physical space.
- The five-year survival rate for all cancers (among Caucasians) contracted in 1960 was 39 percent—today it is more than 60 percent.

- In 1960, 38 percent of working-age women were in the labor force—today, 60 percent are in the labor force; also in 1960, the average worker spent four more hours on the job per week than he or she does today.
- The annual number of person-miles traveled per capita increased by 38 percent between 1969 and 1990, mostly because of lengthening distances between work and home.

Whether these or any other historic social, economic, or technological changes substantially altered the vulnerability of the nation to climate change is a matter of debate. A number of more recent changes, many as dramatic as those witnessed over the past 50 years, will alter the setting in which the impacts of climate change will happen, and they will influence the degree to which adaptation is successful. It is important, therefore, to take these societal changes into account when speculating on the nature of adaptation to climate change. For example, the simple fact that more people are living on the earth now than ever before and that societies have amassed unprecedented wealth suggests that exposure of life and property to climate risk has increased. As working hours have shortened and leisure time has grown, Americans are also spending increasing amounts of time engaged in climate-sensitive recreation, which brings more people in contact with natural hazards. In addition, an extraordinary number of Americans have migrated to coastal regions (particularly the Southeast) in recent decades, increasing the population exposed to sea-level rise and coastal storms (Neumann et al., 2000). Likewise, development in river floodplains is increasing, putting more people and property at risk from flooding.

On the other hand, societies that have acquired greater wealth and technology also have a greater ability to absorb or respond to potential impacts of climate change. For example, although vulnerability to tropical diseases may have increased, the U.S. public health system appears capable of containing outbreaks of infectious diseases, although not eliminating all risk from them (Balbus and Wilson, 2000).

In the case of changes in the agricultural sector, U.S. agriculture in the latter half of the 20th century made unprecedented improvements in productivity. Crop yields have increased by an average of 2 percent per year since 1940 (Huffman and Everson, 1992; Adams et al., 2001). In the future, continued improvements in yields are expected, although perhaps not at such a rapid pace. In addition, increased agricultural efficiency has resulted in a reduction of acreage cultivated. Further gains in efficiency should continue the trend toward reduction. Moreover, the growing demand for urban development will likely reinforce this trend.

II. What History Tells Us about Adaptation to Climate Variability

Historic responses to changes in socioeconomic or environmental conditions can serve as analogues for social adaptation to future climate change. Although historical environmental changes were not—until recently—caused by anthropogenic climate change, many are similar to climate change because they were gradual and irreversible or resulted in large changes in the location of activities. For example, the nation's natural resource managers, including farmers, foresters, civil engineers, and their supporting institutions, have been forced to adapt to numerous historical challenges either to overcome adversity or to remove important impediments to sustained productivity. Many analysts argue that the ways in which those managers and institutions responded to past challenges may provide insights into how they might respond in the future to climate variability and change (Rosenberg, 1982; Glantz, 1988; Easterling, 1996). The following case studies illustrate the potential for technology, human ingenuity, and institutional innovation to deal with changes analogous to climate change: translocation of crops to new environments; resource substitution in response to scarcity; and response to geophysical events similar to climate change.

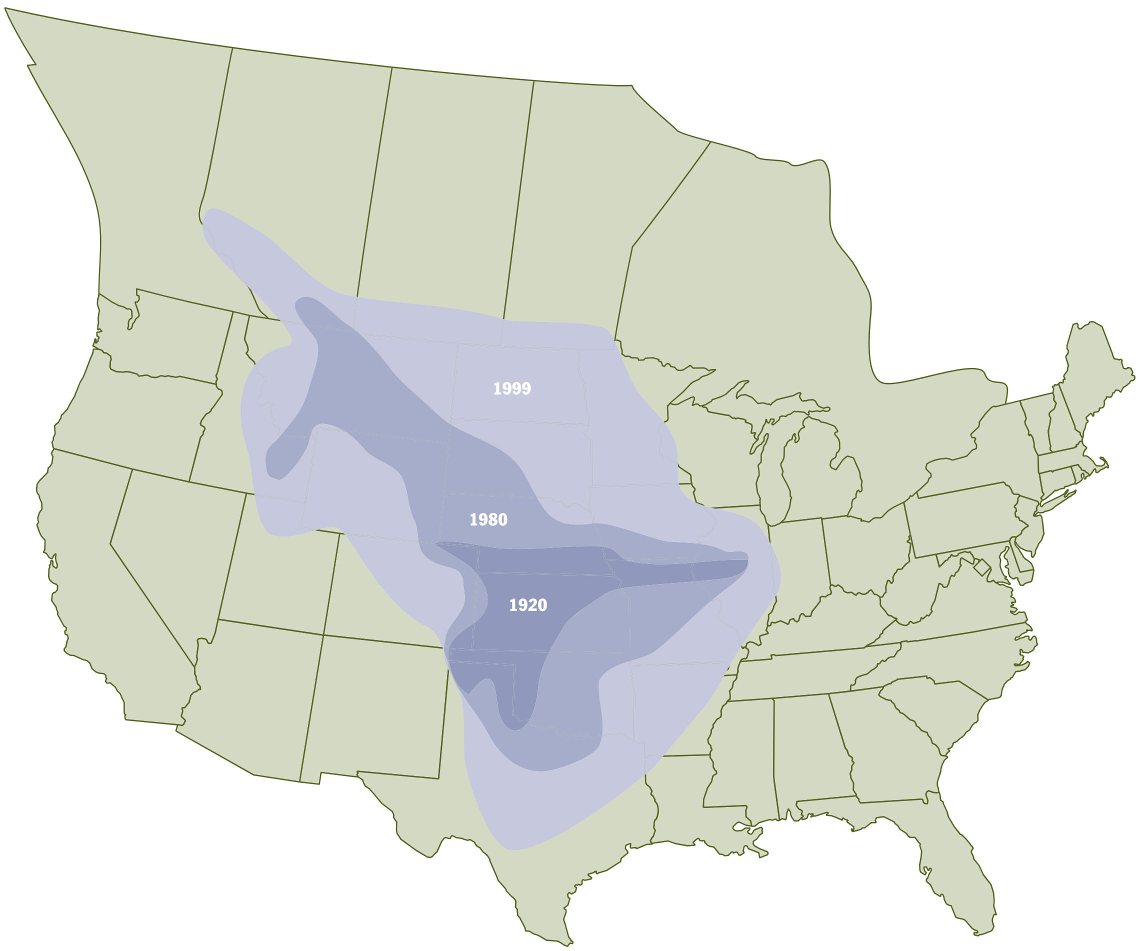
A. Crop Translocation: Winter Wheat in the United States

Most crop species have been successfully translocated thousands of miles from their regions of origin by resourceful farmers, thus exposing the crops to climate change by virtue of changing geography. Translocation requires plant material and cultural practices to adapt to climatic conditions that often differ significantly from those in their regions of origin. The translocation of hard red winter wheat across the prairies of the American Great Plains is a case in point.

Hard red winter wheat consistently accounted for about half of all wheat produced annually in the United States in the 20th century (Briggle and Curtis, 1987). Over the period from 1920 to 1999, the northern boundary of the winter wheat zone migrated northward into a climate that was about 4.5°C (8°F) cooler and 20 percent drier than the climate for the wheat zone in 1920 (Figure 1). The southward expansion of winter wheat has not been as extensive as the northward one, but average annual temperatures at the current southern boundary of the winter wheat production zone are more than 2°C (4°F) higher than those of the 1920 southern boundary. Thus, winter wheat has adapted to cooler, warmer, and drier climates in its century-long expansion.

Figure 1

Changes in the Primary Winter Wheat Production Zones from 1920-1999



Note: The above figure depicts temporal changes in the primary production zone for hard red winter wheat from 1920 to 1999. Although confined during the early 20th century to the central plains states, the production zone expanded south and, particularly, north in subsequent decades due to adaptive actions taken to improve winter wheat productivity under a broader range of environmental conditions.

Source: Adapted from Rosenberg (1982)

What happened to encourage this expansion? Selective breeding for cold-hardy varieties helped the northern expansion of winter wheat. Savdie et al. (1991) found that the trapping of drifting snow over fields to increase moisture infiltration and direct, no-till seeding of winter wheat into stubble immediately after harvest of the previous crop (a practice known as "stubbling-in") reduced the risk of winterkill and permitted northern expansion of the crop to include most of western Canada's agricultural area. Breeding for disease resistance helped the southern expansion. Dalrymple (1988) demonstrates a steady increase in the diversity of winter wheat cultivars planted by American farmers throughout the 20th century. Cox et al. (1986) traced the historical genetic diversity of winter wheat and found that diversity is increasing; they argue that greater genetic diversity provides raw material for further genetic progress. Increasing diversity resulted in the development of wheat cultivars that were more finely tuned to their local environments.

B. Resource Substitution in Response to Scarcity: Dryland for Irrigated Agriculture in the Great Plains

Climate is an important resource in the growth of a crop; it is as important an input as fertilizer or pesticide to successful farming. Moreover, when climate variability disrupts the delivery of climate resources, such as in periods of drought, production costs may rise, causing a decrease in farm revenues. Persistent disruption of climate resources induces farmers to substitute more reliable resources for riskier ones. Consider, for example, the experience of Great Plains farmers in coping with the highly variable precipitation of that region.

Irrigation water has become a widely used substitute for inadequate or unreliable precipitation in the Great Plains since World War II. As long as irrigation water was abundant and cheap, it lowered production costs relative to revenues, giving Great Plains farmers a large comparative advantage. However, scarcity of irrigation water acts like drought in rain-fed regions. Glantz and Ausubel (1984), in a study focusing on the recent agricultural experience with the Ogallala Aquifer of the Great Plains, argue that declining irrigation groundwater can serve as a useful analogy to a gradual decrease in precipitation. The aquifer is a large geologic formation of porous sand that underlies approximately 225,000 square miles of the Great Plains (Wilhite, 1988). Recharge rates are very low, and lateral movement within the aquifer is slow. Groundwater utilization, primarily for irrigation, rose steadily from 7 million acre-feet in 1950 to 21 million acre-feet in 1980 (Wilhite, 1988). These withdrawals caused the saturated thickness of the aquifer to decline by as much as 25 to 50 percent since the 1940s, especially in the southern Great Plains (High

Plains Associates, 1982; Lehe, 1986). Lehe (1986) notes that groundwater declines in the aquifer caused irrigation pumping costs to rise, because pumping water from lower depths requires more fuel.

Kromm and White (1986) cataloged adaptations to declining groundwater levels adopted by farmers across the High Plains Aquifer and ranked the adaptations in terms of desirability for adoption. They report that the two leading adaptations preferred by water users were to increase irrigation efficiency and to practice conservation tillage. Lehe (1986) shows a dramatic increase in the use of low-pressure irrigation systems in the southern Plains states and a switch to low-water-intensity crops such as wheat when aquifer levels dropped. Nellis (1987) demonstrates a 5.5 percent decline in the amount of irrigated acreage in southwestern Kansas between 1977 and 1983, accompanied by a switch to low-water-intensity crops. Some farms failed during the reversion, but those that survived emerged healthy and remain competitive, although their yield expectations were lowered.

C. Sea-Level Rise Analogue: The Rising Great Salt Lake

Societies respond to climate change, but often not in the most efficient manner possible. Thus the process of adaptation can often be a case of "muddling through." Incremental decisions may be adopted to address immediate threats, but changes that could address long-term threats, but may be politically difficult to adopt, are avoided.

Between 1982 and 1986, the Great Salt Lake rose 12 feet due to heavy precipitation in northern Utah (see Morrisette, 1988). This rise resulted in flooding and damage to lakeshore mineral industries, highways and railroads, ecosystems, wildlife and recreation areas, and residential developments bordering the lake. The Great Salt Lake's level had not risen substantially before 1982, and models based on the previous 30 to 40 years of data predicted variability in lake levels only as high as 4,202 feet. Problems arose when actual lake-level variability exceeded historical and modeled variability—by 1986, the actual level reached almost 4,212 feet.

When the lake began rising in 1982, decision-makers assumed it was a one-season anomaly, and chose to take no action. As the lake continued to rise over the next several years, the state government faced uncertainty regarding the nature of the lake change (whether it was an anomaly or a trend). The government decided to adopt a "wait and see" approach to dealing with the problem, choosing short-term structural mitigation over long-term adaptations. The state pursued immediate fixes such as diking and raising highways. These fixes addressed the immediate lake-level rise, but did not necessarily protect the infrastructure from future rises. These solutions also failed to address threats to shoreline development.

As the Great Salt Lake continued to rise in 1986, however, the state government decided to construct a system to pump excess water to a large adjacent evaporative pond that would increase the effective evapotranspiration rate and lower the lake, at a cost of $60 million. Shortly after the pumping project was constructed, precipitation subsided, the lake level began dropping, and the project was then criticized as unnecessary. Interestingly, this pumping project was engineered to be effective in reducing lake levels up to 4,215 feet. If the lake continued to rise above this level—only 3 feet above the high mark in 1986—the pumping project would have no longer been able to reduce the level further. Thus, the project that many viewed as a long-term solution was only effective within a relatively small range of conditions, illustrating the limitations of even long-term structural fixes if actual variability exceeds anticipated limits.

An alternative adaptation option that was proposed, The Beneficial Development Area (BDA), would have established floodplain and hazard zones in the region. The BDA, which potentially would have removed land from development, was proposed by the Federal Emergency Management Agency (FEMA) and had some support at the local level. Localities were reluctant to adopt it, however, because they were wary of surrendering autonomy or restricting development in valuable lands.

D. Case Study Lessons

Unlike the elegance and simplicity of models, case studies demonstrate that actual adaptation can be complex, varied, and imperfect. All three cases illustrate that society has a high capacity for adaptation and *eventually* can make adaptations to accommodate changing conditions. The case study of translocation of crops demonstrates that the agricultural sector can expand the range of certain crops to include climates that are as different as the levels of climate change projected to occur over the next few decades. The Great Plains example shows that adaptations can happen in response to resources becoming limited. The Great Salt Lake example shows that society can, to some degree, address immediate and pressing problems brought about by a changing climate.

Yet these examples, particularly the last two, demonstrate that adaptation is not necessarily seamless or efficient and can be filled with many mistakes and costs. The Great Plains adaptation was necessitated by what could be termed a maladaptation (Burton, 1996). Mining of the water in the High

Plains aquifer was not (nor is) sustainable. Farmers were able to use an inexpensive but not inexhaustible resource. Once sufficiently depleted, alternatives had to be found. To be sure, adaptations were made. Yet, greater foresight and prudence in using a non-renewable resource could have avoided the problems that came down the road. Imposing climate change on top of existing maladaptations can make coping more difficult and expensive.

The Great Salt Lake example is an interesting study of what Glantz (1988) would refer to as "muddling through." At first, decision-makers considered the lake's rise to be an extreme event and anticipated that conditions would soon return to "normal." Perhaps this view reflected the "wishful thinking" of the decision-makers and possibly the sentiments of the wider community—completely understandable positions in the face of significant scientific uncertainty about the fate of the lake. However, though "muddling through" is not unusual, it can impede recognition of long-term change. This can result in delayed actions and, consequently, higher adjustment costs (or incurred damages). In the Great Salt Lake, adaptations were made incrementally to address problems as they arose, but decision-makers had difficulty with anticipatory adaptations to address risks from a continued rise in lake levels. They avoided the BDA, perhaps because it would have resulted in short-term economic harm. The investment in the pumping station turned out to be costly and, ultimately, unnecessary for the immediate problem. However, given the potential for a continued rise in lake levels, the investment still may have been appropriate. Such large investments, which could be necessary for adaptation to climate change, can be risky for decision-makers. Governments may have more incentive to engage in incremental responses that provide only short-term solutions rather than more comprehensive changes that can better position society to cope with larger events in the future.

On the whole, the case studies suggest that society has a substantial capacity to adapt to climate change but may in many instances fall short of using the capacity to its full extent. The necessity of coping with adverse impacts from climate change will force adaptations, but decision-makers may miss many opportunities to adapt more effectively and efficiently.

III. Reactive Adaptation: How Successful Will It Be?

A central question in the assessment of the potential impacts of climate change to the United States is the extent to which adaptation can reduce the vulnerability of societal systems. A review of quantitative studies of reactive adaptation to climate change can help assess whether reactive adaptation may be successful in offsetting adverse impacts of climate change. The literature as a whole offers an opportunity to garner broader lessons concerning the general effectiveness of reactive adaptation.

A. Reactive Adaptation as Assessed in Quantitative Studies

The published literature offers limited analysis on what damages would occur to U.S. societal systems if there were no adaptation to future climate change, and it does not address the extent to which damages could be avoided and the cost of such avoidance measures. The analysis necessary to compare scenarios with and without adaptation has only been conducted for coastal resources and agriculture. Given that these are societal sectors that demonstrate high potential for adaptation, analysis of the relative effectiveness of adaptation in these sectors alone should not be extrapolated to other sectors—such as natural ecosystems—where adaptation may be less successful.

Coastal Development

A small number of studies analyze the implications of sea-level rise for coastal communities and the potential for adaptation to ameliorate damages. Yohe (1989) estimates that a half-meter rise in sea level would place $185 billion of property and infrastructure in jeopardy by 2100,[1] and a one-meter rise in sea level would place $429 billion in jeopardy by 2100. Titus and Greene (1989) estimate that the financial cost of protecting all developed areas from a half-meter sea-level rise would be $50 to $66 billion, and protecting against a one-meter sea-level rise would cost $115 to $174 billion. This analysis suggests that appropriate adaptation could reduce the severity of damages to development by about three-fifths to three-quarters, compared with no adaptation. Neumann et al. (2000) point out that some areas

1. Cost estimates are presented in 2000$, adjusted using consumer price indices as reported in CEA, 2003.

may have relatively low property value relative to the cost of protection and thus further savings are possible by limiting the scope of protection to exclude low value areas. Therefore, the relative reduction in damages from adaptation could be larger. However, even areas with relatively low property values may be valued for cultural, ecological, or aesthetic reasons. The Cajun parishes of the low-lying Louisiana bayous are a prime example.

Agriculture

The U.S. National Assessment of the Potential Consequences of Climate Variability and Change examined the effect of climate change on agricultural production in the United States under two model scenarios—the relatively dry Canadian Climate Model (CCM) and the relatively wet Hadley model (HadCM2) (Reilly et al., 2001). The results comparing dryland crop yields for climate change without adaptation and climate change with adaptation appear in Table 2. Such adaptations account for adjustments made at the farm level; they do not account for shifts in production in response to changes in relative yields domestically or in response to changes in foreign trade (e.g., Adams et al., 1995). Such production shifts could further reduce losses or increase gains from climate change. Moreover, the models

Table 2

Projected National Average Change in Dryland Yields over the 21st Century

Crop	CCM without adaptation	CCM with adaptation	HadCM2 without adaptation	HadCM2 with adaptation
Cotton	+96	+96	+82	+82
Corn	+23	+24	+34	+34
Soybeans	+30	+64	+76	+97
Hard red spring wheat	-4	+14	+30	+36
Hard red winter wheat	-1	+13	+55	+59
Soft wheat	+3	+4	+20	+21
Durum wheat	-5	+12	+30	+33
Sorghum	+21	+87	+70	+96
Rice	-8	+4	+10	+18
Barley	+25	+133	+132	+197
Oats	-2	+24	+101	+106
Silage	+18	+20	+32	+32
Hay	-1	-1	+15	+15
Sugar cane	-5	+7	+8	+16
Sugar beet	+11	+11	+24	+24
Potatoes	-25	-20	-3	+1
Fresh oranges	+91	+91	+69	+69
Processed oranges	+120	+120	+49	+49
Fresh grapefruit	+101	+101	+60	+60
Processed grapefruit	+112	+112	+53	+53
Pasture	+20	+20	+38	+38

Note: Values represent percent changes in crop yields from 2000 to 2090 resulting from climate change with and without adaptation.

Source: Reilly et al. (2001)

do not account for future discoveries in agricultural science and technology that will almost certainly provide new options for adaptation.

The table shows that yields for most crops may increase in response to climate change without adaptation, although yields for some may decrease. In all cases (except for hay under the Canadian model), adaptation may reverse losses. In about half of the cases, adaptation may result in larger yield increases. Reilly et al. (2001) further demonstrate that the average increase in yield brought about by adaptation is 7 to 15 percent.

Similarly, Tol et al. (1998) reviewed two studies of U.S. agriculture—a study of climate change in the Missouri, Iowa, Nebraska, and Kansas region (the MINK study; Easterling et al., 1993), and a reassessment of economic effects of climate change on U.S. agriculture (Adams et al., 1995). The review shows adaptation reducing adverse effects of climate change by 29 to 60 percent in the MINK study (but still yielding net losses) and reversing losses in the economic reassessment study.

Although limited in number, these studies covering the coastal and agricultural sectors show that adaptation can substantially reduce adverse impacts or even turn losses into gains. These studies, however, assume a gradual change in climate and no change in climate variability. It is also important to keep in mind that the results are based on modeling, and models tend to assume perfect information or perfectly rational behavior. The real world is less elegant and simple; actual adaptations may be less effective or more costly than the models suggest. Nonetheless, models provide useful insight into the potential for adaptation.

B. Effectiveness of Reactive Adaptation—General Findings

Can the United States adapt to climate change without incurring excessive social and environmental costs? As mentioned above, limited quantitative information is available to address this question. However, on a qualitative basis, some general conclusions can be drawn regarding the capacity of the United States to adapt to future climate change. Adequate adaptive capacity is required across a range of scales from the micro (place-based) to the macro (national). Reactive adaptation by society depends on a number of determinants of adaptive capacity identified by Yohe and Tol (2002) and supplemented here:

- The path of climate change;
- The portfolio of tools for adaptation;

- The uptake of adaptive strategies; and

- Human and social capital stock and risk-spreading institutions.

The above factors are summarized in the following sections.

The Path of Climate Change

The more rapid and varied the change in climate, the more challenging it will be for society to adapt. The path of climate change incorporates the rate of change, the variability of change, and the magnitude of change (e.g., whether climate becomes monotonically wetter or drier, or whether it fluctuates). Experience with historical analogs of climate change suggests that agricultural and other societal land-use systems are fully capable of responding to long-term change that occurs gradually and consistently. Given the time to depreciate and replace aging capital stock with new stock and production systems, there is little reason to doubt the ability of American farmers to switch to crops that are better adapted to the changing climate, assuming, of course, that such changes are supported by prevailing economic conditions. The key will be the successful identification of the signal of climate change such that farmers make the right decisions in a timely way. If farmers fail in this regard, then they may face substantial costs of adapting. The same conclusions apply to the replacement of coastal infrastructure and buildings in response to climate variability and sea-level rise.

A more rapid rate of climate change is likely to make adaptation more difficult and result in net damages. One of the underlying problems with a more rapid change is that the pace of adaptation needs to speed up. With a more rapid change in climate, infrastructure and other investments will need to be replaced or modified more rapidly and, in many cases, before the end of design lifetimes are reached. Replacing investments early will also increase the cost of adaptation.

Changes in variability, especially increases in extreme events, likely would pose an even greater challenge for adaptation. Extreme events such as floods and droughts cause extensive damage to many parts of society, and thus a critical issue for adaptation is the degree to which frequency, intensity, and persistence of extreme events change. Such changes portend a more difficult and costly transition compared with that based solely on marginal changes in average conditions.

Studies of agriculture have projected that larger magnitudes of climate change (e.g., 4–5°C or 7–9°F) would lead to a decline in marginal production, even under optimistic assumptions about adaptation

(NAST, 2000; Mendelsohn, 2001). Higher magnitudes of sea-level rise translate to, at a minimum, greater risk of flooding and exponential increases in coastal protection costs. Larger magnitudes of change in climate will likely mean more frequent and intense extreme events, even if the variance does not change.

Although the literature indicates that societal systems may be able to cope with climate change under certain circumstances, even a relatively gradual change in climate (e.g., a 2°C or 4°F warming over a century) may overload many species' and ecosystems' ability to adapt. A 2°C (~4°F) warming will shift climate zones in the United States by approximately 100–150 miles. Many species, particularly vegetation, will be unable to migrate at a rate fast enough to keep up with the shifting climatic zones. In addition, human development already severely constrains the ability of many species to adapt to climate change—populations have been reduced and fragmented by development, stressed by pollution, and barred from migration by cities, towns, agricultural areas, and roads. Furthermore, climate change will likely facilitate the introduction and dominance of invasive species more adapted to the new climatic conditions, presenting additional risks to the survival of native species. In general, climate change is expected to result in a loss of biodiversity in the United States.

Box 1

Adaptation in Developing Countries

Adaptive capacity is not equally distributed worldwide. For many societal sectors that are sensitive to climate change such as agriculture, water resources, and human health, the vulnerability of the United States (and other developed countries) is substantially lower than the vulnerability of developing countries. The two main reasons for their greater vulnerability are their sensitivity and exposure and their lower adaptive capacity. Developing countries have a far larger proportion of their economies in climate-sensitive activities such as agriculture. They also face more adverse impacts in this sector. For example, grain crop yields in low latitudes are more likely to be reduced as a result of climate change than grain crop yields in middle and high latitudes (see McCarthy et al., 2001, for more discussion). Negligible increases in temperature in the already warm tropics, home to the majority of developing nations, likely will push crops into physiological stress. This alone severely constrains adaptive capacity.

Developing countries also have greater vulnerability to climate change because they have less adaptive capacity than do developed countries. Smit et al. (2001) identify the determinants of adaptive capacity: economic resources, technology, information and skills, infrastructure, institutions, and equity.

Developed countries generally possess more of these determinants than developing countries. Developed countries have higher income per capita than developing countries (e.g., the countries belonging to the Organization for Economic Cooperation and Development—generally considered to be the developed countries—possess 30 percent of the world's population and 70 percent of the world's income). These countries tend to have the best technology, the highest level of schooling and training, the best access to information, the most developed infrastructure, and the most stable and effective institutions. It is interesting, however, that equitable distribution of income does not appear to be correlated with level of development. Many developing countries have less income disparity than a number of OECD countries (World Resources Institute, 2003).

On the whole, because developing countries tend to possess less adaptive capacity than developed countries, it is reasonable to expect that adaptation would be less effective in coping with adverse effects of climate change.

Even where regions on the whole may be able to successfully adapt to a limited climate change, specific individuals and communities could still be displaced and harmed by climate change. Of particular concern are those communities that have strong ties and associations with specific areas and resources that are exposed and sensitive to climate change (e.g., through sea-level rise, increased drought, extreme heat), derive a high share of their income from climate sensitive activities such as agriculture or fishing, and lack financial and other means to adapt to change.

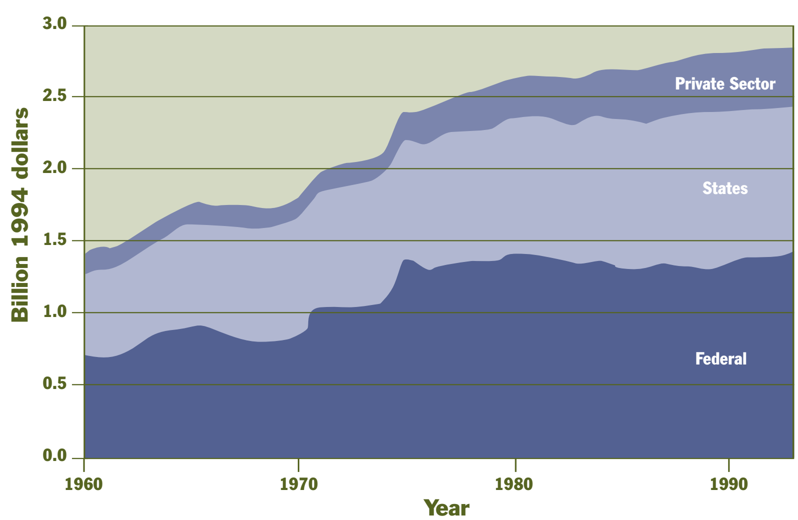
In addition, this paper's optimism about the ability of the United States to adapt to a gradual warming should not be extrapolated to the ability of developing countries to adapt to climate change. Developing countries face a different set of challenges with climate change that briefly are outlined in Box 1.

The Portfolio of Tools for Adaptation

The United States currently is endowed with a large portfolio of tools for adapting to climate change. Results of model simulations of simple reactive agronomic strategies, such as switching crops and cultivars, planting earlier, and changing land-use allocations, suggest that the nation's farmers have a high potential to adjust to the early stages of warming. Moreover, the nation's water managers and other natural resource professionals have developed strategies for coping with climate risk. Such strategies, which include increasing storage, improving conservation, and increasing water transfers may provide a measure of protection against climate variability and a first line of defense against climate change. Much is still unknown, however, such as the long-term success of these tools for mitigating

Figure 2

Support for **Agricultural Research (1960-94)**



The above figure depicts long-term changes in federal, state, and private funding for agricultural research over three decades.

Notes: Annual expenditures adjusted for inflation by cost-of-research deflator, includes funds for USDA research agencies (Agricultural Research Service, Economic Research Service, and National Agricultural Library) and cooperative state research.

Source: Economic Research Service. Data derived from Alston and Pardey (1995).

climate change, and the ease with which the tools will be employed. In particular, it is not clear if these tools alone will be sufficient to adapt to a rapid change in climate or a change that involves a significant increase in intensity or frequency of extreme events.

The research and development sectors may yield new technologies and practices providing more tools for adaptation—for example, genetically modified crops and animals, and innovative applications of knowledge gained by mapping plant and animal (including the human) genomes to reduce vulnerability to climate and related stresses. These advances bode well for successfully coping with future climate transitions, as long as the pace of climate change is not excessive. However, the rate of technological innovation is tied to the level of federal, state, and private investment committed to research. According to the U.S. Department of Agriculture's Economic Research Service, public (state and federal) research expenditures for agriculture rose 3-4 percent per year from 1960 to 1980 (Fuglie et al., 1996). Since 1980, however, government real investment in agricultural research has been essentially flat (Figure 2). This is not an encouraging sign for the agricultural sector's capacity to adapt to climate change.

The portfolio of adaptation tools will also depend on the perceptions and values of the broader society. Social acceptability of technology given real or perceived risks can be a significant barrier to technological adoption and diffusion, to wit, the rapid and nearly universal decline of the nuclear power industry in the United States. Advances in agricultural biotechnology have shown significant promise in altering the sensitivity of agricultural crops to a variety of factors, including climactic factors such as temperature and drought. However, social and cultural attitudes toward food and the types of technologies that are used in its production have raised concerns about potential heath risks, risks to genetic diversity, and aesthetic characteristics. It is too early to project the long-term future of the technology. However, the current resistance by Asian and European consumers and the potential that continues for rejection by the U.S. consumers may well slow research and the deployment of these technologies.

Uptake of Adaptive Strategies

Resource managers and policy-makers will be challenged to identify, observe, and react to climate change appropriately. This challenge stems partly from the difficulty in properly identifying and distinguishing climate change from natural climate variability (Schneider et al., 2000). There is some indication that the process of adapting to climate change has already begun, among both societal and natural systems. However, the earlier case study of the Great Salt Lake exemplifies the trouble that managers may encounter with detecting a climate-change trend from background climatic fluctuations. Compounding this identification challenge, inappropriate management strategies and institutional constraints on decision-makers—such as the need to give due consideration to the rights of property owners—may result in delayed adaptation and outright maladaptation—that is, long-term adaptation to short-term climate variability that is inconsistent with long-term climate change. Over the long term, some inefficiency in adaptation is bound to happen, at least initially. In the case of agriculture, Schneider et al. (2000) demonstrate that crop yields could be reduced by several percentage points if farmers delay their response to climate change or misread the direction that climate change takes. Another critical issue is how quickly new technologies will be diffused into common use.

Yet another important facet is the role of public policy in promoting or inhibiting adaptation. Policies that encourage experimentation and change could promote adaptation, while those that discourage change can discourage adaptation. For example, agricultural policies that reward farmers for planting specific crops in specific locations can discourage farmers from changing their planting regime in response to climate change. Water policies that encourage users to consume or waste water can inhibit the adoption of water-saving technologies and practices and even the transfer of water to more efficient uses in response to climate change. In contrast, water allocation policies that enable prices to fluctuate with water availability and allow water to be traded among users tend to encourage more efficient use of water. Market-oriented water transfers can provide valuable flexibility in adapting to changes in water scarcity. The value of this flexibility and the adaptive capacity it provides must, however, be weighed against the possible adverse and unintended consequences such transfers often entail because of water's interconnectedness to water users whose values are difficult to reflect in economic markets (e.g., the value of instream flows for fish and wildlife habitat, the aesthetic and spiritual values held by some groups, and the value of quantity and quality changes to downstream water users).

It is important to note that complete adaptation by all regions, populations, or individuals is not a necessary condition for society on the whole to adapt successfully. Indeed, successful adaptation can entail a loss of livelihood and migration for many people. For example, the agricultural sector is expected to adapt to climate change in part by expanding production in northern parts of the United States and reducing production of many crops in many southern areas (NAST, 2000). This geographic shift could result in reduction of acreage or loss of employment for many farmers in areas that experience shrinking production. Other sectors are equally confronted by challenges of climate change (e.g., see the discussion about water resources in Box 2).

Box 2

Water Resources: A Focal Point of Adaptation

Throughout human civilization and settlement, water has been a focus of human adaptation to the natural world. A key precursor to permanent settlement, finding and developing reliable water supplies are among the first issues a community must address. Historically, water supply needs were addressed by deciding where to locate settlements—for example, communities have almost always been located on or near a source of water such as a river or spring. Close proximity to water, however, often entails risks. Settlements along rivers are subject to seasonal variations in stream flow and most dramatically to the periodic flooding that generally characterizes rivers and streams. Communities usually develop strategies to cope with the variability of water supply: storing water during periods of abundance for use during periods of scarcity, and developing protective systems that mitigate damages during floods.

Balancing the benefits of proximity and risks of flood, however, is often a complex community decision that is made all the more difficult under climate change. A challenge is, therefore, presented to communities in adapting these balancing methods to the prospect of climate change. Consider the recent flooding that occurred in the Mississippi and Missouri rivers and the challenges to policymakers in deciding where and how re-development should be permitted. In 1993, water flows in the Mississippi and Missouri watersheds exceeded all measures ever recorded for the basin—precipitation levels, river flows and heights, duration of flood flows, area flooded, and economic impacts. The flooding was the most costly in U.S. history, with damages estimated between $12 billion and $16 billion (Interagency Floodplain Management Review Committee, 1994). Some have speculated that the event was a once in 500 years occurrence; however, such a statistic has meaning only if the underlying hydroclimatic conditions have been and continue to be fundamentally stable. How prone to failure is that assumption, especially given that the historical record in most cases spans only about 100 years?

Studies of climate change impacts on U.S. water resources suggest that vulnerabilities are keenly tied to runoff changes and can vary greatly within and across regions (Hurd et al. 1999a, 2004; Lettenmaier et al., 1999). Estimates are highly sensitive to assumptions about future demands and to the potential for adaptive responses to mitigate impacts. For example, if water supplies become limited, to what extent do communities implement measures to reduce inefficient water uses? Further complicating an estimation of impacts is a host of other factors, stressors, and their interactions. Many regions, for example, are confronting the stresses of diminished water quality and heightened competition for available water supplies. These conditions add to the vulnerability that communities face in adapting to climatic change (Hurd et al., 1999b).

Planning and management actions can increase the resiliency and adaptability of water systems in the face of expected climate change. Proactive options use robust methods for risk management in water resources, and help insure cost-effective responses to climate change (Major, 1998). Flexible new developments in water institutions, including the increasing use of markets and privatization, are helping shape the opportunities for anticipatory adaptation options. U.S. examples include free-market water purchases in California, privatization of water system operations in Atlanta and other cities, and privatization of a regional sewage system in the Milwaukee metropolitan area (Metropolitan Water District of Southern California, 2001; United Water, 1998; Milwaukee Metropolitan Sewage District, 1999, respectively).

Two schools of thought on the adaptive capacity of water resources and systems have emerged. The first believes that water managers already have the necessary tools to cope with climatic change. Schilling and Stakhiv (1998), for example, argue that key responses to climate change are virtually the same as responses to existing variability: upgrade supply-side and demand-side measures and add flexibility to institutions to better cope with social and environmental changes. The other school, however, attaches greater significance to the changing fundamentals being introduced into the climate system. A shift in the climate paradigm increases the uncertainty. No longer can the historical record be relied on to guide the design, construction, and planning of water projects. This school has less confidence that sufficient time and information will be available before the onset of significant or irreversible impacts. Proponents of this view argue that "complacency on the part of water managers may lead to the failure to anticipate impacts that could be mitigated or prevented by actions taken now" (Gleick and Adams, 2000). In its report on climate change and U.S. water resources, the U.S. National Water Assessment Group sides with the latter group and cautions that "sole reliance on traditional management responses is a mistake" (Gleick and Adams, 2000). The assessment group advises that the uncertainties of climate

Box 2

Water Resources: A Focal Point of Adaptation (cont.)

change could require the development of new approaches and technologies associated with water systems and use, as well as efforts and project designs that exceed those planned for in addressing current climate variability. The downside of complacent (or reactive) responses of water managers and reliance on traditional tools alone is the lost opportunities for cost-effective prevention or mitigation of severe impacts. Rather, the assessment group advocates an anticipatory response on the part of water resource managers, policy-makers, and infrastructure designers.

IV. The Case for Proactive Adaptation

The nature and extent of expected climate change may reveal inadequacies in existing institutions and reactive responses. Waiting to act until changes have occured can be more costly than making forward-looking responses that anticipate climate change, especially with respect to long-lived assets and infrastructure such as bridges and dams, coastal development, and floodplain development. A "wait-and-see" approach would be particularly unsuccessful in coping with:

- Irreversible impacts, such as species extinction or unrecoverable ecosystem changes;
- Unacceptably high costs and damages, such as inappropriate coastal zone development that exposes lives and property to intense storm damages; and
- Long-lived investments and infrastructure that may be costly or prohibitive to change in response to climate change (Smith, 1997).

Proactive adaptation, unlike reactive adaptation, is forward-looking and takes into account the inherent uncertainties associated with anticipating change. Successful proactive adaptation strategies are therefore flexible; that is, they are designed to be effective under a wide variety of potential climate conditions, to be economically justifiable (i.e., benefits exceed costs), and to increase adaptive capacity.

When and where climate change risks loom large, long-run societal goals may benefit from a thorough and comprehensive consideration of the adequacy of institutions and infrastructure in providing necessary services in light of climate change. Perhaps the clearest and strongest cases for incorporating proactive adaptation into long-term planning are those of long-lived investments and the design and organization of institutions.

Proactive adaptation could be best facilitated through a range of possible mechanisms including knowledge and learning, risk and disaster management and response, infrastructure planning and development, institutional design and reform, increased flexibility of sensitive managed and unmanaged systems, avoidance of maladaptation, and technological innovation. In addition, all of these mechanisms are routinely influenced or governed by public institutions and public policy, allowing governments to play an active role in enhancing the uptake of proactive adaptation strategies. These mechanisms and their intersection with public policy are briefly discussed below. Box 4 presents some examples of reactive and anticipatory adaptations that are already occurring in the United States.

A. Knowledge and Learning

Knowledge is key to adaptive capacity (Smith and Lenhart, 1996; Smit et al., 2001). Knowledge is dynamic; it accumulates through observation, monitoring, and analysis. It can also degrade, however, if the learning process is neglected. For example, knowledge degrades if monitoring and data collection systems collapse, if research and development are not continually supported, if literacy and education levels diminish, or if basic societal infrastructure decays.

Adapting knowledge proactively involves choosing the type and level of learning from a spectrum of pathways, ranging from passive to active learning. Passive learning is akin to reactive adaptation. Passive knowledge is desirable when short-run and long-run priorities are in agreement and when reaction times for adjusting to external disturbances are relatively swift. In the context of climate change, passive learning presupposes that climate change will behave in a predictable and smooth manner and that any surprises can be "muddled through" with minimal disruption. However, climate change could involve sudden and unpredictable changes in extreme events, which could limit the capacity of nonstructural changes to cope with impacts.

At the other end of the spectrum, active learning is more experimental. Active processes may involve periodic testing such as providing a shock to the system and observing the resulting behavior. Such testing supports the possibility for feedback to update and revise the system, thus enlivening the process of adaptive capacity building.

B. Risk and Disaster Management and Response

Proactive adaptation to climate change may necessitate periodic reassessment of the adequacy and preparedness of relief systems and programs, particularly in light of changing frequency and intensity of extreme events. Governments and insurance companies provide relief for such extreme climate events as hurricanes, floods, and droughts. Even though these programs appear to be the very essence of reactive response, they can involve risk-reduction measures. For example, insurance companies may require the adoption of certain practices to reduce exposure of people and property to climate extremes or they drop insurance.

Insurance rates are driven by actuarial tables and probability estimates, which heavily depend on knowledge and information gathered from government agencies. Updating risk tables may require anticipation of future changes in risk. Disaster assistance agencies such as FEMA must be able to assess their financial exposure to risk in order to identify budgetary needs.

An example of proactive preparedness is the ability to fight and control fires during the explosive summer fire season. With hotter summers, the extent, magnitude, and length of the fire season can reasonably be expected to rise (e.g., Malcolm and Pitelka, 2000; NAST, 2000). Proactive adaptation, therefore, may include fire mitigation programs such as prescribed burns and land use controls.

C. Infrastructure Planning and Development

Among the most visible components of adaptive capacity are the infrastructure systems that support economic activities and social functioning. In many cases, flexibility, durability, and resiliency to climatic variability and change can be enhanced via changes in infrastructure design characteristics and building codes (Toman and Bierbaum, 1996), similar to the approach taken in earthquake-prone areas. Weighing the economic tradeoffs, however, is the principal difficulty. Designing infrastructure to enhance flexibility, durability, and resiliency is often relatively inexpensive (National Research Council, 1992). Getting the balance correct is challenging in the face of an uncertain climate future and a planning process that often focuses on short-term and least-cost solutions. Questions of the "sufficiency" of building design and the possibility of ex post adaptation (i.e., reactive adaptations) are pertinent and contribute to the complexity. (See Box 3 for a discussion of sea-level rise adaptation issues.)

D. Institutional Design and Reform

Institutional effectiveness is another key element to promoting adaptive capacity. Institutions can provide information to affected actors on how climate is changing and how they can alter their behavior to adapt to the change (Ribot et al., 1996; Smith and Lenhart, 1996; O'Riordan and Jordan, 1999). For example, weather services can provide information on changes in climate means and variability, while agriculture extension services can inform farmers about changes in crop varieties and practices that may be better suited to changing climate conditions.

Box 3

Adaptation to Sea-Level Rise in the United States

Current actions to adapt to sea-level rise and coastal erosion provide interesting insight into measures that might be undertaken to adapt to accelerated sea-level rise associated with climate change. Sea-level rise is one effect of climate change that is readily understandable by coastal inhabitants and, in some cases, already an important part of coastal management. Some forward-looking states and communities have begun to recognize the inertia of sea-level rise: a certain measure of accelerated sea-level rise will happen, regardless of short-term actions that might be taken to mitigate greenhouse gas emissions and the anticipated impacts. Adaptation measures taken now can minimize property damage, reduce eventual protection costs, and maximize continuing ecological health of coastal resources. Whether initiated by governments or individuals, many of these actions can justifiably be termed adaptations to sea-level rise, although in some cases the stated motivation for the action may be linked to other coastal processes (e.g., shore erosion).

Land-use planning and acquisition programs in a few states acknowledge the increasing vulnerability of coastal resources to advancing seas. In New Jersey, for example, the Coastal Blue Acres land acquisition program was initiated in 1995 to acquire lands in coastal areas that have been damaged by storms, that may be prone to storm damage, or that buffer or protect other lands from storm damage. The funds are now exhausted, and the acquired lands are being used for recreation and conservation. This anticipatory approach to limiting the potential for future property damage meshes well with the state's land-use planning, initiated to ensure consistency between local development plans and state infrastructure investments. Through this comprehensive planning, New Jersey has more clearly delineated areas for future development and clarified expectations of where the state plans to support investments such as roads and beach nourishment in the coastal zone.

Other states also have clear coastal policy statements that encourage coastal landowners to act in ways that anticipate sea-level rise. In Rhode Island, shoreline armoring (e.g., seawalls) has been explicitly prohibited along much of the open ocean shoreline and in some back bay areas as well. Texas has established a rolling easement—an entitlement to public ownership of property that "rolls" inland with the coastline as sea level rises (Titus, 1998). This measure is one of the more explicit adaptive measures being undertaken because of its direct link with sea-level rise. Other states employ setbacks (Bernd-Cohen and Gordon, 1999), a less desirable measure, because once property is developed there is no mechanism for acknowledging a continuing advance of the seas. The development line becomes fixed, and it may eventually require expensive fortification against the sea. Finally, a few states have initiated requirements for local governments to explicitly acknowledge sea-level rise (e.g., North Carolina) or storm evacuation potential (e.g., Florida) in their comprehensive land-use management plans.

At the federal level, one encouraging program is FEMA's Community Rating System. In exchange for implementing government-sponsored planning and risk communication programs, residents in participating counties receive reductions in their annual National Flood Insurance Program premiums. Among other measures, the program encourages communities to preserve open space, impose development restrictions (frequently through zoning), and relocate high-risk structures.

In a few cases, individuals are also taking adaptive actions. Many coastal landowners, for example, practice small-scale erosion-control measures such as erecting sand fencing, and others are accommodating rising sea level by elevating their structures and incorporating "tear-away" walls on ground floors to accommodate storm surges. In some cases, these measures are encouraged by financial incentives provided by national flood insurance reforms. Another factor encouraging individuals to adapt to coastal hazards is an increasing concern among private insurers about writing general homeowners policies for properties in coastal zones, even for properties as far as 1,000 feet inland.

In addition, some landowners are banding together to take collective action. In Santa Barbara, California, residents raised $3.5 million to purchase a 69-acre coastal parcel to prevent development, creating a recreation area and erosion buffer in the process (Heinz Center, 2000).

Nonprofit land trusts and conservancies are also beginning to take notice of sea-level rise. These organizations, committed to long-term ecological health through land conservation, have a strong interest in understanding how coastal ecologies may be altered by a rising sea, especially with regard to their land acquisition and conservation efforts. For example, The Nature Conservancy's Global Climate Change Initiative includes a project in the

Box 3

Adaptation to Sea-Level Rise in the United States (cont.)

Albemarle Sound area of North Carolina and Virginia. The Nature Conservancy is protecting lands in this area to enable species and their surrounding systems to migrate inland and upstream in response to future sea-level rise.

As sea-level rise accelerates, there will be a growing need for a more concerted effort to coordinate actions and undertake adaptive plans on a broader scale. The first step in most areas is awareness of the threat. Adaptive planning measures can then be taken to ensure an efficient sea-level rise response strategy that combines retreat, accommodation, and protective strategies. While the ability to forecast sea-level rise with great accuracy over long time scales is limited, the advantage of time, the high value of coastal property, and the relative predictability of sea-level rise compared to other effects of climate change mean adaptation is likely to be a good investment.

Prepared by James E. Neumann, Industrial Economics Inc.

Institutions can also inhibit adaptation. One way they do so is to distort information that could encourage adaptation. Water allocation institutions that fix the prices consumers pay effectively mask changes in water availability that could be communicated to consumers through changes in prices. Institutions can also encourage behavior that is destructive or risky. For example, flood insurance programs can encourage development in flood-prone areas by insuring homes against flood risk, rather than having consumers bear the full risks and therefore presumably adopt more risk-averse behavior (see the discussion of maladaptation below).

Changing institutions so they can better address climate change can be a difficult and costly matter. Institutions are long-lived and often lack the internal mechanisms for self-assessment and revision. Vested interests are often effective at lobbying to protect and preserve their economic stakes and the real or perceived "value" of their property, the value of which in turn is determined in part by the economic benefits of the institution or program (Buchanan and Tullock, 1962). Thus, maintaining or restoring institutional effectiveness raises its own challenges, not the least of which are claims by property owners for "takings" compensation.

Better design, reform, and coordination of government policies and programs can be appropriate vehicles for proactive adaptation. The most suitable reforms can also generate additional benefits that improve resource planning and economic efficiency. Hurd et al. (1999a, 2004) and Frederick and Gleick (1999) suggest that improving the viability and functioning of active water markets, for example, contributes to increased water use efficiency under current climate conditions, and also helps mitigate the adverse impacts of climate change. Such "no regrets" or win-win approaches lead the list of improvements and changes worthy of consideration (Scheraga and Grambsch, 1998).

E. Increased Flexibility of Sensitive Managed and Unmanaged Systems

Increasing the flexibility of vulnerable managed and unmanaged systems to withstand changes in climatic conditions may be an effective proactive response to climate change. For example, the adaptive capacity of managed systems that are sensitive to climatic conditions, such as agriculture and water delivery infrastructure, may be helped by measures that enhance these systems' resilience to climate variability and change (i.e., ability to

Box 4

Is the United States Already Adapting to Climate Change?

Societies and natural systems are always adapting to climate fluctuations and variability. With the climate changing, partly as a result of increased greenhouse gas concentrations, it should be no surprise that adaptations to climate change are being made. Whether these are conscious choices to adapt to climate change induced by anthropogenic activity is not known.

Consistent with expectations, two types of adaptations are being made. The vast majority of adaptations are reactive. For example, *The Washington Post* reported that some companies are investing in weather insurance to protect against losses from higher temperatures (Schneider, 2001). In addition, some farmers have expressed interest in purchasing drought and flood resistant seeds in response to increased weather extremes. Insurance companies are becoming more concerned about increased risks from extreme events. Such behavior is quite similar to responses to climate variability, but there does appear to be a growing recognition that average and extreme climate conditions are changing. This recognition appears to be incorporated more and more into decisions that are sensitive to climate. For example, McBeath (2003) found that institutions managing Alaska's transportation systems are incorporating climate change into decisions with long lifetimes (e.g., 50 to 75 years) but not shorter-term decisions.

There is also growing evidence that the natural world is changing in response to climate change. (The observed effects of climate change on ecosystems in the United States is a topic of a separate report in preparation.) For example, Parmesan (1996) found that the location of Edith's checkerspot butterflies has shifted northward along the West Coast of the United States, apparently in response to increased temperatures, while several studies found that a number of species of birds are laying eggs earlier and migrating north earlier in the year (Bradley et al., 1999; Brown et al., 1999; Dunn and Winkler, 1999).

In addition to the many examples of reactive adaptation, there are some examples of people consciously anticipating future climate change in their decisions. One of the more interesting examples comes from Massachusetts, where the Massachusetts Water Resource Authority (MWRA) has designed a sewage treatment plant for the greater Boston metropolitan area with sea-level rise in mind. The plant is located on Deer Island, in Boston Harbor. Raw sewage collected from communities on shore is pumped under Boston Harbor and up to the treatment plant. After the wastes are treated, the effluent is discharged into the harbor through a gravity outflow (i.e., a downhill pipe). The MWRA originally planned to lower the level of Deer Island about half a meter to be closer to sea level. This would reduce the costs of pumping untreated sewage from the shore up to the treatment plant. However, design engineers were concerned that sea-level rise would necessitate construction of a wall around the treatment plant to keep the sea out. The effluent would then need to be pumped up over the wall and into the harbor. Such a pump would cost several hundred million dollars. To avoid such a cost, even though it might be decades before it would need to be installed, the designers decided to leave the island at a higher elevation.

recover quickly from a shock such as an extreme climate event; Klein and Tol, 1997). Enhanced resilience already benefits these systems under current climate variability, and even more benefits may be witnessed under future climate change. For example, allowing markets to signal whether water supplies are limited or available can enable consumers to react quickly to changes in supply.

Natural ecosystems are particularly vulnerable to climate change, owing largely to their significant sensitivity and exposure and to their limited capacity to adapt to even moderate change. Some policy measures may reduce the vulnerability of natural systems. For example, efforts that reduce current stresses such as habitat fragmentation and pollution can enhance the strength and resilience of natural systems, resulting in stronger populations and enhanced capability to respond to climate change. Land-use policies that conserve migration corridors may also improve the likelihood that some species survive as climate changes (Parmesan and Galbraith, 2004).

F. Avoidance of "Maladaptations"

The avoidance of "maladaptations" is an important consideration for climate change adaptation. Maladaptations are situations where management of natural resources is already leading to undue harm to ecosystems or society (Burton, 1996). For example, the current practices of development of low-lying coastal areas and areas prone to flooding and the continued cropping of marginal agricultural areas are examples of trends that increase exposure to current climate and climate change risks. Limiting development of low-lying coastal areas, applying innovative approaches such as "rolling easements" (Titus, 1998), or using such programs as the Conservation Reserve Program to discourage cropping of marginal agriculture areas are examples of approaches that can address maladaptation.

G. Technological Innovation

Technological change is a principal route of many recent human adaptations. Innovations in transportation, agriculture, and information systems have advanced adaptive capacity in significant ways. Technology has propelled U.S. agriculture to ever-greater production levels over the past century (Cochrane, 1979). Adams et al. (2001) and Reilly (1999) conclude that technological innovation coupled with appropriate advances and changes in management will enable the U.S. agricultural system to rise to the challenges posed by climate change. However, that is predicated on maintaining and possibly enhancing both private and public research capacity, which may require that both government and industry take proactive positions.

H. The Role of Public Policy

Public institutions and policies wield considerable power in shaping technology development, resource and land use, information collection and dissemination, risk management, and disaster relief. As a result, governments can substantially influence the magnitude and distribution of climate change impacts and social preparedness. For example, the U.S. experience during the Dust Bowl era of the 1930s shaped the design and direction of government efforts to assist in managing the nation's soil and agricultural resources. Research was pursued to understand the causes and contributing factors of the Dust Bowl, and to develop technologies, management systems, and support programs to minimize the reoccurrence of such a calamity. Had the reaction been limited to simply providing immediate disaster relief and restoration of existing practices, the country might have faced an even worse set of outcomes during the severe drought that later hit the region in the 1950s. However, that potentially more extreme disaster was avoided because of the proactive steps that had been taken by the federal government (Cochrane, 1979; CAST, 1992).

V. Conclusions

As the climate-change research and policy communities fully confront the challenges of understanding and managing adaptation to climate change, the issues framed in this report provide important insights concerning the information needed to make appropriate policy choices regarding adaptation. The following conclusions provide initial guidance to those communities:

1) Adaptation and mitigation are necessary and complementary for a comprehensive and coordinated strategy that addresses the problem of global climate change. By lessening the severity of possible damages, adaptation is a key defensive measure. Adaptation is particularly important given the mounting evidence that some degree of climate change is inevitable. Recognizing a role for adaptation does not, however, diminish or detract from the importance of mitigation in reducing the rate and likelihood of significant climate change.

2) The literature indicates that U.S. society can on the whole adapt with either net gains or some costs if warming occurs at the lower end of the projected range of magnitude, assuming no change in climate variability and generally making optimistic assumptions about adaptation. However, with a much larger magnitude of warming, even making relatively optimistic assumptions about adaptation, many sectors would experience net losses and higher costs. The thresholds in terms of magnitudes or rates of change (including possible non-linear responses) in climate that will pose difficulty for adaptation are uncertain. In addition, it is uncertain how much of an increase in frequency, intensity, or persistence of extreme events the United States can tolerate.

3) To say that society as a whole "can adapt" does not mean that regions and peoples will not suffer losses. For example, while the agricultural sector as a whole may successfully adapt, some regions may gain and others may lose. Agriculture in many northern regions is expected to adapt to climate change by taking advantage of changing climatic conditions to expand production, but agriculture in many southern regions is expected to contract with warmer, drier temperatures. Individual farmers may lose their livelihoods. In addition, other individuals or populations in these and other regions can be at risk, because they could be adversely affected by climate change and lack the capacity to adapt. This is particularly true of relatively low-income individuals and groups whose livelihoods are dependent on resources at risk from climate change.

4) Adaptation is not likely to be a smooth process or free of costs. While studies and history show that society can on the whole adapt to a moderate amount of warming, it is reasonable to expect that mistakes will be made and costs will be incurred along the way. People are neither so foolish as to continue doing what they have always done in the face of climate change, nor so omniscient as to perfectly understand what will need to be done and to carry it out most efficiently. In reality, we are more likely to muddle through, taking adaptive actions as necessary, but often not doing what may be needed for optimal or ideal adaptation. Additionally, adaptation is an on-going process rather than a one-shot instantaneous occurrence. Compounding society's shortcomings, a more rapid, variable, or generally unpredictable climate change would add further challenges to adaptation.

5) Effects on ecosystems, and species diversity in particular, are expected to be negative at all but perhaps the lowest magnitudes of climate change because of limited abilities of natural systems to adapt. Although biological systems have an inherent capacity to adapt to changes in environmental conditions, this capacity is limited. Given the rapid rate of projected climate change, adaptive capacity of many species is likely to be exceeded. Furthermore, the ability of ecosystems to adapt to climate change is severely limited by the effects of urbanization, barriers to migration paths, and fragmentation of ecosystems all of which have already critically stressed ecosystems independent of climate change itself.

6) Institutional design and structure can heighten or diminish society's exposure to climate risks. Long-standing institutions, such as disaster relief payments and insurance programs, affect adaptive capacity. Coastal zoning, land-use planning, and building codes are all examples of institutions that can contribute to (or detract from) the capacity to withstand climate changes in efficient and effective ways.

7) Proactive adaptation can reduce U.S. vulnerability to climate change. Proactive adaptation can improve capacities to cope with climate change by taking climate change into account in long-term decision-making, removing disincentives for changing behavior in response to climate change (such as removing subsidies for maladaptive activities), and introducing incentives to modify behavior in response to climate change (such as the use of market-based mechanisms to promote adaptive responses). Furthermore, improving and strengthening human capital, through education, outreach, and extension services, improves decision-making capacity at every level and increases the collective capacity to adapt.

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notes

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