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North America

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EXECUTIVE SUMMARY

North America has experienced challenges posed by changing climates and changing patterns of regional development and will continue to do so. Varying impacts on ecosystems and human settlements will exacerbate subregional differences in climate-sensitive resource production and vulnerability to extreme events. Opportunities may arise from a warming climate, and some innovative adaptation strategies are being tested as a response to current challenges (e.g., water banks), but there are few studies on how these strategies could be implemented as regional climates continue to change. Recent experience demonstrates high capability in emergency response to extreme events, but long-term problems remain.

Climate Trends and Scenarios

North America has warmed by about 0.7°C during the past century and precipitation has increased, but both trends are heterogeneous (e.g., seasonal reductions in precipitation in some areas).

For a range of emission scenarios produced for this Third Assessment Report, model results suggest that North America could warm by 1–3°C over the next century for a low-emissions case (B1). Warming could be as much as 3.5–7.5°C for the higher emission A2 case. Published regional impact studies have used climate scenarios with global temperature changes that are similar to these new cases, but regional scenarios may not be directly comparable.

Key Regional Concerns

Water Resources

Changes in precipitation are highly uncertain. There is little agreement across climate scenarios regarding changes in total annual runoff across North America.

The modeled impact of increased temperatures on lake evaporation leads to consistent projections of reduced lake levels and outflows for the Great Lakes–St. Lawrence system under most climate change scenarios (medium confidence). The only exception is the HadCM2 transient scenario incorporating IS92a sulfate aerosol emissions, which suggests slight increases in lake levels and outflows.

Where snowmelt currently is an important part of the hydrological regime (e.g., Columbia basin), seasonal shifts in runoff are likely, with a larger proportion of runoff occurring in winter, together with possible reductions in summer flows (high confidence).

Adaptive responses to such seasonal runoff changes could include altered management of artificial storage capacity, increased reliance on conjunctive management of ground and surface water supplies, and voluntary water transfers between various water users. It may not be possible, however, to avoid adverse impacts on many aquatic ecosystems or to fully offset the impacts of reduced summer water availability for irrigation and other out-of-stream and instream water uses.

Where lower summer flows and higher water temperatures occur, there may be reduced water quality and increased stress on aquatic ecosystems (medium confidence).

Possible changes in the frequency/intensity/duration of heavy precipitation events may require changes in land-use planning and infrastructure design to avoid increased damages arising from flooding, landslides, sewerage overflows, and releases of contaminants to natural water bodies.

Responses to recurring and emerging water quality and quantity problems will provide opportunities to develop and test adaptive management options.

Natural Resources

Forests

Climate change is expected to increase the areal extent and productivity of forests over the next 50–100 years (medium confidence). Extreme and/or long-term climate change scenarios indicate the possibility of widespread decline (low confidence).

Climate change is likely to cause changes in the nature and extent of several "disturbance factors" (e.g., fire, insect outbreaks) (medium confidence). Of particular interest in North America are changes in fire regimes, including an earlier start to the fire season, and significant increases in the area experiencing high to extreme fire danger. The long-term effects of fire will depend heavily on changes in human fire management activities, which are uncertain, especially in remote boreal forests.

There is a strong need for a long-term comprehensive system to monitor forest "health" and disturbance regimes over regional scales that can function as an early warning system for climate change effects on forests.

Protected Areas

Climate change can lead to loss of specific ecosystem types, such as high alpine areas and specific coastal (e.g., salt marshes) and inland (e.g., prairie "potholes") wetland types (high confidence). There is moderate potential for adaptation to prevent these losses by planning conservation programs to identify and protect particularly threatened ecosystems.

Food and Fiber

Agriculture

Food production is projected to benefit from a warmer climate, but there probably will be strong regional effects, with some areas in North America suffering significant loss of comparative advantage to other regions (high confidence). There is potential for increased drought in the U.S. Great Plains/Canadian Prairies and opportunities for a limited northward shift in production areas in Canada (high confidence). Crop yield studies for the United States and Canada have indicated a wide range of impacts. Modeled yield results that include direct physiological effects of carbon dioxide (CO_2), with sufficient water and nutrients, are substantially different from those that do not account for such effects. Economic studies that include farm- and agricultural market-level adjustments (e.g., behavioral, economic, and institutional) indicate that the negative effects of climate change on agriculture probably have been overestimated by studies that do not account for these adjustments (medium confidence). However, the ability of farmers to adapt their input and output choices will depend on market and institutional signals, which may be partially influenced by climate change.

Production Forestry

Lands that are managed for timber production are likely to be less susceptible to climate change than unmanaged forests because of the potential for adaptive management. However, when the possibility of replanting with incorrect species is considered, economic impacts could become negative.

Carbon Sequestration—Adaptation Issues

Increased interest in agricultural sinks for carbon sequestration includes proposed use of reduced-tillage practices in North America. Negative consequences may include increased use of pesticides, reduced yields, and increased risk for farmers (medium confidence). Potential benefits include reduced input costs, increased soil moisture, and reduced soil erosion (high confidence).

Marine Fisheries

Climate-related variations in the marine environment—including changes in sea-surface temperatures, nutrient supply, and circulation dynamics—play an important role in determining the productivity of several North American fisheries (high confidence).

Projected climate changes have the potential to affect coastal and marine ecosystems, with impacts on the abundance and spatial distribution of species that are important to commercial and recreational fisheries. The degree of impact is likely to vary within a wide range, depending on species and community characteristics and region-specific conditions. These impacts are complex and difficult to observe, so climate variability constitutes a significant source of uncertainty for fishery managers. Recent experiences with Pacific salmon and Atlantic cod suggests that sustainable fisheries management will require timely and accurate scientific information on environmental conditions that affect fish stocks, as well as institutional flexibility to respond quickly to such information.

Human Health

Increased frequency and severity of heat waves may lead to an increase in illness and death, particularly among young, elderly, and frail people, especially in large urban centers. The net effect of reduced severity of extreme cold is likely to have a beneficial effect. Acclimatization may be slower than the rate of ambient temperature change.

Increased frequency of convective storms could lead to more cases of thunderstorm-associated asthma. More frequent flood events and other extreme events may result in an increase in deaths, injuries, infectious diseases, and stress-related disorders, as well as other adverse health effects associated with social disruption, environmentally forced migration, and settlement in urban slums.

Vector-borne diseases, including malaria and dengue fever, may expand their ranges in the United States and may develop in Canada. Tick-borne Lyme disease also may also expand its range in Canada. However, socioeconomic factors such as public health measures will play a large role in determining the existence or extent of such infections. Diseases associated with water may increase with warming of air and water temperatures, combined with heavy runoff events from agricultural and urban surfaces.

Respiratory disorders may be exacerbated by warming-induced increases in the frequency of smog (ground-level ozone) events, acidic deposition, and particulate air pollution.

Human Settlements and Infrastructure

Potential impacts of climate change on cities include fewer periods of extreme winter cold; increased frequency of extreme heat; rising sea levels and risk of storm surge; and changes in timing, frequency, and severity of flooding associated with storms and precipitation extremes.

Communities can reduce their vulnerability to potential adverse impacts from climate change through investments in adaptive infrastructure. These adaptations can be expensive. Rural, poor, and indigenous communities may not be able to make such investments. Furthermore, infrastructure investment decisions often are based on a variety of needs beyond climate change, including population growth and aging of existing systems.

Changes in the frequency, severity, and duration of extreme events may be among the most important risks associated with climate change. The rising cost of natural disasters in North America illustrates the vulnerability of current settlement practices. Human alterations of natural systems—such as drainage basins, barrier islands, and coastal margins—influence the impact of extreme weather hazards. Adaptations such as levees and dams often are successful in managing most variations in the weather, but they can increase vulnerability to the most extreme events.

Tourism

Shifts in temperature and precipitation patterns would lead to shifts in outdoor tourism and recreation opportunities (e.g., winter sports, fishing, parks, beaches). The extent to which ecological changes in parks will affect tourism is uncertain. Future shifts in water management, in response to development pressures as well as climate change, also could affect recreational opportunities and associated property values. Opportunities and challenges for recreational industries and destination areas need to be assessed in a systematic manner before net economic impacts can be reported with sufficient confidence.

Public and Private Insurance and Disaster Relief Systems

Inflation-corrected, weather-driven losses have been increasing in North America over the past 3 decades (high confidence). Both exposure and financial surplus of private insurers (especially property insurers) and reinsurers have been growing, and weather-related profit declines and insolvencies have been observed. Insured weather-related losses in North America (59% of the global total) are increasing with affluence and as populations continue to move into vulnerable areas. Insurer vulnerability to these changes varies considerably by region. Insurers are adversely affected by increased variability or actuarial uncertainty of weather-related events. Governments play a key role as insurers and/or providers of disaster relief, especially in cases in which risks are deemed to be uninsurable by the private sector.

Canada and the United States have different loss profiles (high confidence). In both countries, the nature of weather-related exposures and losses is diverse, ranging from property damages to business interruptions caused by electric power or communication system damage (as in the 1998 ice storm). U.S. government insurance programs for crops and floods have not been profitable and in some cases have encouraged more human activity in at-risk areas. In the absence of similar programs in Canada, government disaster relief programs have paid roughly 86% of flood losses over the past 2 decades. There remains an important tension between the allocation of such risks between private insurers and the public sector, and the effects of climate changes (e.g., coastal erosion) would increasingly stress government programs.

Recent extreme events have led to several responses by insurers, including increased attention to building codes and disaster preparedness, limiting insurance availability or increasing prices, and establishment of new risk-spreading mechanisms. Insurers can play an important role in climate adaptation and mitigation. However, because their actuarial outlook is based on past climatic experience and forward-looking modeling studies are just now beginning to be used, the potential for surprise is real.

Adaptation Potential and Vulnerability

Case studies for various North American subregions and border regions illustrate how the changing nature of climate-society relationships is influencing the nature of vulnerability, climate-related impacts, and adaptive responses. These cases include observed extreme events and potential responses to climate change scenarios. Increased levels of development may reduce vulnerability in some cases (e.g., agriculture) and increase or change vulnerability in others (e.g., Columbia basin water management).

The nature of observed damages reflects the increasing demands that society is placing on natural resources and systems that are sensitive to extreme events, as climate change is superimposed on complex environmental problems (e.g., coastal eutrophication in the Gulf of Mexico).

Climate-related consequences for water, health, food, energy, insurance, governments, and human settlements are likely to require substantial institutional and infrastructure changes in some cases. The short period of time required to make infrastructure adjustments is likely to require new institutions to cope with rapid and sweeping change. The example of new “water markets” in the western United States illustrates an adaptive measure that also may lead to concerns about accessibility of this essential commodity for lower income people, as well as conflicts about social priorities in its allocation (e.g., farms vs. residential use).

Determining responses to scenarios is a long process that requires dialogue with stakeholders. They understand the goals, objectives, and constraints driving the development, management, and operation of resource production and maintenance systems. This interdisciplinary and intercultural dialogue has the potential for improving sharing of information and enhancing its use in decisionmaking at various scales.

15.1. The North American Region

15.1.1. Previous Work

This chapter offers an assessment for Canada, the United States, and three border regions—the Arctic, U.S.–Mexican, and U.S.–Caribbean borders. More detailed assessments for the Arctic, Mexico, and the Caribbean appear in Chapters 16, 14, and 17, respectively.

The IPCC's *Special Report on Regional Impacts of Climate Change* (IPCC, 1998) provides a review of more than 450 research publications concerned with impacts in North America, generally covering work done during 1975–1997. That review focused on six key sectors:

- Hydrology and water resources
- Nonforest terrestrial and forested ecosystems
- Food and fiber, including agriculture, production forestry, and fisheries
- Coastal systems
- Human settlements and industry
- Human health.

Our update of key regional concerns (see Section 15.2) uses similar categories, with a couple of modifications. First, we consider coastal and marine ecosystems together with terrestrial ecosystems, within the review of natural resources (Section 15.2.2). Second, human settlements are reviewed as a separate category, with extended discussion of infrastructure (Section 15.2.5). Impacts on tourism and insurance are treated separately (Sections 15.2.6 and 15.2.7, respectively). We also include a series of subregional cases that highlight adaptation challenges and opportunities (see Section 15.3).

This categorization of key regional concerns in North America reflects growing interest in higher order impacts. Recent increases in financial losses from extreme weather events (hurricanes, winter storms, floods) have raised new questions about changing frequencies of atmospheric events superimposed on changing development and investment patterns. In the United States, there were 28 such events during the 1980–1997 period with losses exceeding US$1 billion. The most costly were the droughts and heat waves of 1988 and 1990, Hurricane Andrew in 1992, and the 1993 Mississippi River flood, with combined costs exceeding US$100 billion. In Canada, the 1996 Saguenay flood and 1998 ice storm in Ontario and Quebec each cost more than US$0.7 billion (CDN$ 1 billion) (Etkin, 1998). It is important to understand the extent to which these loss trends hinge on changes in climate or changes in vulnerability that may be independent of any changes in climate.

In recent years, the North American nations have undertaken intensive region-specific assessments of impacts and vulnerability (Canada Country Study, U.S. National Assessment, regional case studies). Although some of these assessments are still in progress at this writing, several themes have emerged. The involvement of stakeholders (commercial entities, local and regional governments, natural resource managers, and citizens) has brought new perspectives and refocused the definition of research questions. In nearly all regions, stakeholders perceive changes in variability to be far more threatening than decadal-scale gradual change. Many stakeholders see limited problems in adaptation and possible benefits to slow predictable change. However, there may be appreciable changes in ecosystem distributions and water resources, with significant economic impacts, leading to requirements for substantial changes in infrastructure (e.g., in coastal and permafrost regions, major urban centers). There clearly will be winners and losers.

Overall, available information suggests that if projected levels of climate changes occur, North America will become quite a different place.

15.1.2. What is Different about the North American Region?

North America includes economies and resources that might be comparable to those in developed countries and the more developed of the developing countries. Areas within highly urbanized and industrial zones or intensively managed agriculture, forests, and nonrenewable resource extraction all represent large-scale, highly managed resources and human-dominated ecosystems. Within this context, however, there continues to be a great deal of "extensive" land management. Many Canadian and U.S. forests are managed in relatively large tracts compared to other regions and are rather lightly managed aside from harvest schedules. Some are more intensively managed, including post-harvest site preparation for reforestation.

Table 15-1 shows a range of development indicators for Canada and the United States and compares these indicators to Mexico and the rest of the world. Higher levels of resource consumption, urbanization, life expectancy, and gross domestic product (GDP) are obvious, as are the higher rates of CO_2 emissions. At the same time, the two countries also are unusual in preserving extensive rangelands and other landscapes, so a unique feature is the juxtaposition of intensive management with "extensive" management of huge and sparsely populated areas. Some of these areas remain very much a part of the national economy, but other areas are used for subsistence. Areas that are undeveloped or are under aboriginal land claims that support traditional subsistence lifestyles include features that are found in developing country rural economies. These include low levels of built infrastructure, informal barter systems, close ties to the land, and strong historical and cultural attachments to subsistence-based communities, even in the face of opportunities in the modern wage economy.

In wage and nonwage circumstances, climate change scenarios become scenarios of changing opportunities and risks. Given the multi-objective and multi-stakeholder aspects of North American regions, a climate-related change in potential (e.g., longer growing season, higher fire risk, altered hydrological cycle) may not lead to an immediate, linear response by stakeholders (see Section 15.3). An important factor that must be considered

Table 15-1*: Human development in North America.*[a]

Attribute	Canada	USA	Mexico	Rest of World
1995 land area (ha per capita)	31.4	3.4	2.2	2.1
1995 protected areas (ha per capita)	3	0.6	0.1	0.2
1998 internal renewable water (m^3 per capita yr^{-1})	94,373	8,983	4,508	6,332
1987/95 annual freshwater water withdrawal (m^3 per capita)	(Note b)	(Note b)	—	601
1995 electric consumption (kWhr per capita)	17,047	12,660	1,813	1,689
1994 commercial energy use (kg oil-equivalent per capita)	7,854	7,819	—	1,079
1995 CO_2 emission (t per capita)	14.8	20.5	3.5	3.2
1995 population over 65 (% of total)	12.0	12.6	4.5	6.2
1995 life expectancy at birth (yr)	79.1	76.4	73.0	62.9
1995 urban population (% of total)	77	76	61	43
1995 population in cities of 750,000 or more (% of total)	41	42	—	18
1990 labor force in agriculture (% of total)	3	3	22	52
1990 labor force in industry (% of total)	25	26	35	20
1990 labor force in services (% of total)	71	71	42	29
1995 GDP (US$ PPP per capita)	21,916	26,977	3,600	4,851

[a] Data from UNDP(1999), Organisation for Economic Cooperation and Development (<http://www.oecd.org/env/indicators/index.htm>); and Instituto Nacional de Estadistica Geografia e Informatica, Mexico (<http://www.inegi.gob.mx/poblacion/ingles/fipoblacion.html>).
[b] The United Nations has data for Canada and the United States, but they were not included in the report (UNDP, 1999). The report shows use of 1,069 m^3 per capita for industrial countries.
— = data not available.

is the extent to which individual rights are valued relative to community interests in the management of landscapes. Changing vulnerabilities may occur as a result of coupling of management to current climatic variability (e.g., watersheds developed for hydroelectric production and flood control must continue to adjust to seasonal and yearly variations in natural streamflow, as well as changing management objectives).

15.1.2.1. High Level of Intensive Water Management

The water resources of North America have been heavily modified and intensively managed to serve a variety of human purposes. Investments in water control and delivery infrastructure range from small, privately constructed impoundments, diversion works, and levees to major multi-purpose projects constructed by federal, state, or provincial governments. The usable human-made reservoir capacity in North America is equal to approximately 22% of average annual runoff, compared to a worldwide average of 10% (Dynesius and Nilsson, 1994). Development has been most intensive in the United States, where there are approximately 75,000 structures classified as dams, with a combined storage capacity approximating 70% of mean annual runoff, or about 1,300 km^3 (1 billion acre-feet) (Graf, 1999). Current water-management infrastructure has allowed the citizens of North America to make productive use of water and to reduce the adverse impacts of extreme high and low flows—but often at the cost of radically altering the natural functioning of aquatic ecosystems. The design of reservoirs and control structures and current operational protocols are based on the past hydrological record. Stationarity in the statistical characteristics of streamflow typically is assumed to apply for the future operational life of the facility. A change in mean flow or in variability could cause the physical infrastructure to be inadequate for the intended purposes or increase the risk of failure of the water resource system under extremes of drought or flood. In large water systems, such risks are buffered by robustness and resilience in the design of the system (Matalas, 1998); smaller systems may be more vulnerable under climate scenarios beyond those considered in their design.

In addition, North Americans have created laws and institutions that govern allocation of water among competing uses and define the rights and obligations of individuals, government entities, and other organizations with respect to particular water resources. These institutional aspects vary by region and have changed over time, reflecting differences in climatic and historical circumstances and changing societal values. In the western United States and western Canadian provinces, the economic importance of out-of-stream water uses drove the historical development of the prior appropriation system of water law, whereas U.S. states and Canadian provinces east of the 100th meridian generally adhere to riparian or riparian-based permit systems of water law (Chandler, 1913; Hutchins, 1971; Bates *et al.*, 1993; Scott and Coustalin, 1995). Recently, concerns about endangered species, water quality, and other public trust values have led to changes in permitted uses of some water rights in the United States, and environmental legislation is now a powerful force in determining the location, design, and feasibility of new water projects (California Supreme Court, 1983; Wilkinson, 1989; Butler, 1990; Miller *et al*., 1996). A new development in the United States is that some dams are being removed or considered for removal to alleviate impairment of the aquatic ecosystem and to restore fisheries (WWPRAC, 1998).

Because North America's water management institutions and infrastructure evolved partly as adaptations to current climate variability, we expect these investments to be useful in fostering adaptability to some of the effects of long-term climate change. However, to the extent that water management facilities have impaired the health and diversity of aquatic ecosystems, they may exacerbate the adverse environmental consequences of global climate change by reducing the resilience of natural systems to further climatic stress.

15.1.2.2. Urbanization

Within developed regions of North America, one important feature is the high-value concentrated development center or corridor. Proliferation of these centers and corridors (e.g., U.S. Gulf coast, Boston-New York-Washington corridor) can lead to high damage costs from extreme events associated with weather phenomena (see Sections 15.2.5 and 15.2.7).

A second feature concerns extension of urban land use into previously undeveloped or less-developed areas, including agricultural lands, forested areas, wetlands, barrier islands, and other coastal margins. In the case of urban encroachment on forested areas, climate change effects on human use and value of forest ecosystems are likely to be significant but are very poorly understood (Binkley and Van Kooten, 1994). This is a challenge in considering traditional human uses of forests for wood products, recreational space, or environmental protection. A more recent phenomenon that must be considered, however, is the increase in human populations in many forested areas in the mid-latitude regions of North America. For example, in the Colorado Rocky Mountains in the United States, human population is expected to double in the next 20–40 years (Stohlgren, 1999). These population increases will amplify climate-induced stresses on forest habitat and species assemblages. Moreover, these increases will increase the exposure of human populations to climate-induced catastrophic events (e.g., fire, floods).

15.1.2.3. Continental Free Trade

The North American Free Trade Agreement (NAFTA) between Canada, the United States, and Mexico has contributed to several changes in economic activity. One indicator is the recent increase in the population of Mexican states along the U.S.-Mexican border (see Table 15-2), which is at a faster rate than for Mexico as a whole. Such shifts may alter the relationship

***Table 15-2**: Population of Mexican states along the U.S.–Mexican border (data from Instituto Nacional de Estadistica Geografia e Informatica, Mexico, <http://www.inegi.gob.mx/poblacion/ingles/fipoblacion.html>).*

Population	1990	1992	1997	% change
Baja California	1,660,855	1,908,434	2,241,029	+35
Sonora	1,823,606	1,866,757	2,183,108	+20
Chihuahua	2,441,873	2,503,515	2,895,672	+19
Coahuila	1,972,340	2,040,046	2,227,305	+13
Nuevo Leon	3,098,736	3,336,044	3,684,175	+19
Tamaulipas	2,249,581	2,351,663	2,628,839	+17
Total population in Mexico	81,249,645	85,627,971	93,716,332	+15

between regions and their climate, affecting the nature of future climate-related impacts and adaptation responses (e.g., see Section 15.3.2.9).

15.1.3. Past to Present

Society has long viewed climate as "constant"—that is, we expect year-to-year variations, but we expect that the chances of hurricanes, floods, or heat waves don't change with time. The probability of a 100-year event (defined by crossing some threshold—say, 5 cm of rain in an hour) should be a constant. As we have developed longer records of climate—from geologic records in ice cores and sediments to longer and longer instrumental records—we have learned that this assumption of constancy simply is not true. As we look back and see constant change, we should look to the future and expect additional changes to climate and to climate variability.

There have been significant changes (i.e., trends) in North America's climate over the past century. As a whole, North America has warmed by about 0.7°C (Carter *et al*., 2000), although this warming has been quite heterogeneous. For example, the southeastern United States cooled slightly over that same period, although recent decades have seen some warming. There also have been trends in precipitation. Annual precipitation over North America decreased by about 50 mm in the early years of the century and since then has steadily increased by ~70 mm. These trends, like those of temperature, have been fairly heterogeneous. The largest increases have been in the northern Atlantic and Pacific coastal regions. Some regions have experienced seasonal decreases in precipitation. Accompanying these trends in temperature and precipitation, which are fairly well measured, have been changes in cloud cover and humidity, which affect plant growth as well as people's perception of temperature. Inferences from atmospheric CO_2 and satellite data suggest that the northern growing season (the period of active plant growth) has lengthened appreciably over the past decades (Myneni *et al.*, 1997), and data from Alaska show an unequivocal warming trend in the western Arctic (Bering Sea Impacts Study, 1999).

Over the course of the 20th century, there have been several extreme periods in the climate. The drought of the 1930s changed all of North American society. The damage to midcontinental agriculture and communities has consequences even today, through changes in land ownership, government policies, and farmer and merchant perceptions of risk. More recently, there have been major consequences of drought, flooding, tropical storms, and tornadoes. There is no clear evidence of trends in the meteorological risks from "heaviest rainfall category" events or that their frequency has changed over the period of instrumental measurements. However, evidence from the paleorecord documents changes over the past thousands of years that lie outside what our contemporary society can remember. For example, there have been several droughts in California, documented in tree-ring and lake-level data, of more than 80 years' duration (Meko *et al*., 1991). Evidence from the Rocky Mountain and Great Plains regions suggests that there have been long periods in the Holocene (the time since the last glaciation) when these regions were much drier than today (Woodhouse and Overpeck, 1998). These historical events did not happen as a result of anthropogenic impacts but are within the range of natural climate variability; they provide a caution against assuming that tomorrow's climates will necessarily be no less benign than today's.

15.1.4. Scenarios for the Future

At the large scale, and for a range of emission scenarios produced for the IPCC's Third Assessment Report (see Section 3.8), climate model results suggest that North America could warm at a rate of 1–3°C over the next century for a low-emissions case (B1). Warming could be as rapid as 3.5–7.5°C for the higher emission A2 case. Even the B1 case suggests substantially more warming over the next century than we have observed over the past 100 years. In addition, we know that the past century saw changes in temperature, precipitation, and other variables. Climate model predictions of precipitation remain highly uncertain. Many models suggest higher rainfall over North America accompanying warming in simulations of the IS92a emission scenario (Schimel *et al.*, 1996). While some models suggest widespread and substantial increases in rainfall over most of North America, other models suggest a weaker increase in rainfall.

Understanding concurrent changes in regional temperature and precipitation is crucial. Warming with increasing precipitation is likely to increase plant growth, which may increase carbon storage (VEMAP Members, 1995) and may increase pest and pathogen invasion and expansion. Warming with a lesser increase or a decrease in precipitation could cause direct vegetation mortality and increase the risk of wildfire. Variability also plays a role. General increases in temperature and precipitation might increase plant growth, but occasional severe droughts would then maximize the chances of wildfire. Preliminary results from modeling of the United States suggest that projected changes in climate will cause very substantial changes to the distribution and productivity of ecosystems and to disturbance regimes (fire and drought probabilities). Subtropical conditions will extend further north into the United States, with accompanying changes to vegetation, hydrology, and the potential for disease. Changes at the Arctic border suggest changes to the forest-tundra transition region, losses of permafrost, and an altered growing season.

Concern about the spatial uncertainty of model-based climate scenarios has led to various attempts at downscaling global scenarios to regional scales. This can influence the results of impact studies, as illustrated by a recent case study of crop yields in the U.S. Great Plains (Mearns *et al.*, 1999). Furthermore, published regional impact studies have used older global climate scenarios similar to the temperatures resulting from the new emissions cases, but these may not be directly comparable.

15.2. Key Regional Characteristics

15.2.1. Water Resources

Available evidence suggests that global warming may lead to substantial changes in mean annual streamflows, seasonal distributions of flows, and the probabilities of extreme high- or low-flow conditions (Leavesley, 1994; Cubasch *et al.*, 1995; Mearns *et al.*, 1995; Trenberth and Shea, 1997). Runoff characteristics may change appreciably over the next several decades, but in the near term, the hydrological effects of global warming are likely to be masked by ongoing year-to-year climatic variability (Rogers, 1994; Miller, 1997; Matalas, 1998). There is some evidence that the intensity of rainfall events may increase under global warming, as a result of increases in the precipitable water content of the atmosphere (IPCC, 1996; Trenberth and Shea, 1997). This may increase flooding risks in some watersheds. Hydrological changes cannot yet be forecast reliably at the watershed scale, although numerous studies have addressed the potential effects of warming scenarios on water availability in North America (e.g., Mortsch and Quinn, 1996; Melack *et al.*, 1997; Moore *et al.*, 1997; Mulholland *et al.*, 1997; Woodhouse and Overpeck, 1998; Wilby *et al.*, 1999; Wolock and McCabe, 2000). Figure 15-1 summarizes some possible regional hydrological and ecological impacts of climate change identified in recent analyses.

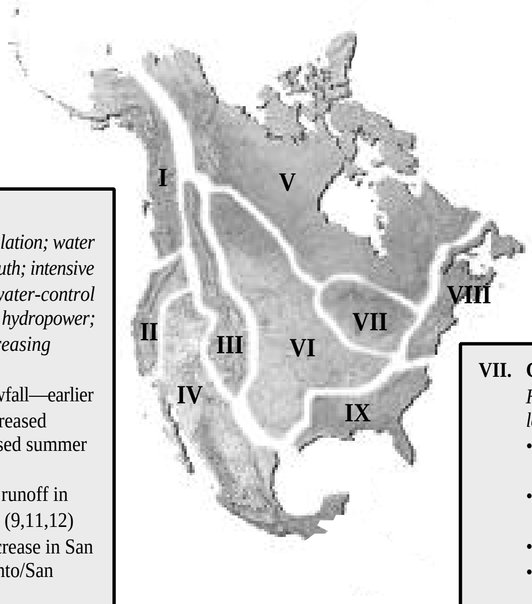
In general, there is greater confidence in projections of seasonal shifts in runoff and related hydrological characteristics than there is in projections of changes in annual runoff. Regional patterns of precipitation change are highly uncertain. Runoff changes also will depend on changes in temperatures and other climatic variables. Warmer temperatures may cause runoff to decline even where precipitation increases (e.g., Nash and Gleick, 1993). Changes in vegetation characteristics will have further, complex impacts on streamflows (Callaway and Currie, 1985; Rosenberg *et al.*, 1990; Riley *et al.*, 1996). Wolock and McCabe (2000) computed annual runoff projections for the 18 major water-resource regions of the continental United States for two GCM scenarios used in the U.S. National Assessment. They found very little agreement between the models—the Canadian Centre for Climate Prediction and Analysis (CCC) model and the Hadley Centre for Climate Prediction and Research (HAD) model—regarding the direction of change in average annual runoff. In addition, most of the projected changes for the next century fell within the range of current variability.

Projections of shorter snow accumulation periods appear to be more robust. Many studies of snowmelt-dominated systems show similar seasonal shifts to greater winter runoff and reduced summer flow (e.g., Cooley, 1990; Lettenmaier and Gan, 1990; Rango and Van Katwijk, 1990; Duell, 1992, 1994; Lettenmaier *et al.*, 1992, 1996; Rango, 1995; Melack *et al.*, 1997; Fyfe and Flato, 1999; Wilby *et al.*, 1999). In mountainous areas of western North America, small high-elevation catchments may contribute the bulk of the flow of major river systems (Schaake, 1990; Redmond, 1998). Although some models predict decreases in snowpack, records from at least one long-term alpine site in the Rocky Mountains show an increase in annual precipitation since 1951 (Williams *et al.*, 1996). Earlier melt-off in combination with either lower or higher snowpack will tend to increase winter or spring flows and reduce summer flows. Warmer temperatures could increase the number of rain-on-snow events in some river basins, increasing the risk of winter and spring floods (Lettenmaier and Gan, 1990; Hughes *et al.*, 1993; Loukas and Quick, 1996). Lower summer flows, warmer summer water temperatures, and increased winter flows are results on which many of the regional ecological impacts identified in Figure 15-1 are based.

Studies based on climate change scenarios from older versions of GCMs that did not include aerosol effects suggest reductions in streamflow and lake levels in many Canadian watersheds, despite scenario increases in annual precipitation (Hofmann *et al.*, 1998). Bruce *et al*. (2000) examined a variety of newer evidence, including temperature and precipitation changes projected by transient runs of seven different atmosphere-ocean GCMs (AOGCMs) with business-as-usual greenhouse gas (GHG) and aerosol increases. They conclude that many areas of Canada, including southwestern Canada and the Great Lakes region, could experience "…reduced total flow, lower minimum flows and lower average annual peak flow" (Bruce *et al.*, 2000).

Open-water evaporation is an important part of the water balance of the North American Great Lakes. Increased evaporation as a result of warmer water temperatures therefore would likely affect future lake levels and outflow into the St. Lawrence River (Mortsch and Quinn, 1996; Mortsch *et al.*, 2000). Most analyses for the Great Lakes suggest declines in lake levels and outflows (Mortsch and Quinn, 1996; Chao, 1999). Chao (1999), for example, examined 10 different transient GCM scenarios (without aerosols) for IPCC decades 2 and 3 and concludes, "In general the decrease in inflows under all the GCM scenarios result in negative impacts to hydropower, navigation and coldwater habitat, and positive ones to shoreline damages." Mortsch *et al.* (2000) compared such early results to results based on transient runs of the CCC model and the HadCM2 model, both of which include aerosol impacts. Whereas the CCC model run suggests declines in lake levels and outflows comparable to the earlier doubled-CO_2 runs (e.g., a 1.01-m decline in the level of Lakes Michigan and Huron by 2050), the HadCM2 model indicates the possibility of a small rise in lake levels and outflows (0.03-m rise in Lakes Michigan and Huron by 2050). Caution is required in interpreting these results because there is substantial uncertainty regarding future sulfate emissions, and projections of aerosol concentrations have declined considerably since these runs were performed (Carter *et al*., 2000).

Arid environments are characterized by highly nonlinear relationships between precipitation and runoff. Thus, streamflows in the arid and semi-arid western portions of North America will be particularly sensitive to any changes in temperature and precipitation (Schaake, 1990; Arnell *et al.*, 1996; Kaczmarek *et*



I. Alaska, Yukon, and Coastal British Columbia

Lightly settled/water-abundant region; potential ecological, hydropower, and flood impacts:

- Increased spring flood risks (1,2)
- Glacial retreat/disappearance in south, advance in north; impacts on flows, stream ecology (2,3,4)
- Increased stress on salmon, other fish species (2,5)
- Flooding of coastal wetlands (5)
- Changes in estuary salinity/ecology (2)

II. Pacific Coast States (USA)

Large and rapidly growing population; water abundance decreases north to south; intensive irrigated agriculture; massive water-control infrastructure; heavy reliance on hydropower; endangered species issues; increasing competition for water:

- More winter rainfall/less snowfall—earlier seasonal peak in runoff, increased fall/winter flooding, decreased summer water supply (6,7,8,9,10)
- Possible increases in annual runoff in Sierra Nevada and Cascades (9,11,12)
- Possible summer salinity increase in San Francisco Bay and Sacramento/San Joaquin Delta (6,13)
- Changes in lake and stream ecology—warmwater species benefitting; damage to coldwater species (e.g., trout and salmon) (6,8,14)

III. Rocky Mountains (USA and Canada)

Lightly populated in north, rapid population growth in south; irrigated agriculture, recreation, urban expansion increasingly competing for water; headwaters area for other regions:

- Rise in snowline in winter-spring, possible increases in snowfall, earlier snowmelt, more frequent rain-on-snow—changes in seasonal streamflow, possible reductions in summer streamflow, reduced summer soil moisture (4,15,16,17,18)
- Stream temperature changes affecting species composition; increased isolation of coldwater stream fish (19)

IV. Southwest

Rapid population growth, dependence on limited groundwater and surface water supplies, water quality concerns in border region, endangered species concerns, vulnerability to flash flooding:

- Possible changes in snowpacks and runoff (20)
- Possible declines in groundwater recharge—reduced water supplies (21)
- Increased water temperatures—further stress on aquatic species (22)
- Increased frequency of intense precipitation events—increased risk of flash floods (23)

V. Subarctic and Arctic

Sparse population (many dependent on natural systems); winter ice cover important feature of hydrological cycle:

- Thinner ice cover, 1- to 3-month increase in ice-free season, increased extent of open water (24,25)
- Increased lake-level variability, possible complete drying of some delta lakes (24,25)
- Changes in aquatic ecology and species distribution as a result of warmer temperatures and longer growing season (25,26,27)

VI. Midwest USA and Canadian Prairies

Agricultural heartland—mostly rainfed with some areas relying heavily on irrigation:

- Annual streamflow decreasing/increasing; possible large declines in summer streamflow (11,17,28,29,30,31,32)
- Increasing likelihood of severe droughts (4,33)
- Possible increasing aridity in semi-arid zones (34)
- Increases or decreases in irrigation demand and water availability—uncertain impacts on farm-sector income, groundwater levels, streamflows, and water quality (29,35,36)

VII. Great Lakes

Heavily populated and industrialized region; variations in lake levels/flows now affect hydropower, shipping, shoreline structures:

- Possible precipitation increases, coupled with reduced runoff and lake-level declines (37,38)
- Reduced hydropower production; reduced channel depths for shipping (4,38)
- Decreases in lake ice extent—some years w/out ice cover (39)
- Changes in phytoplankton/zooplankton biomass, northward migration of fish species, possible extirpations of coldwater species (39)

VIII. Northeast USA and Eastern Canada

Large, mostly urban population—generally adequate water supplies, large number of small dams but limited total reservoir capacity; heavily populated floodplains:

- Decreased snow-cover amount and duration (40)
- Possible large reductions in streamflow (40)
- Accelerated coastal erosion, saline intrusion into coastal aquifers (4,41,42)
- Changes in magnitude, timing of ice freeze-up/breakup, with impacts on spring flooding (41,43)
- Possible elimination of bog ecosystems (40)
- Shifts in fish species distributions, migration patterns (41)

IX. Southeast, Gulf, and Mid-Atlantic USA

Increasing population—especially in coastal areas, water quality/nonpoint-source pollution problems, stress on aquatic ecosystems:

- Heavily populated coastal floodplains at risk to flooding from extreme precipitation events, hurricanes (22,32)
- Possible lower base flows, larger peak flows, longer droughts (44)
- Possible precipitation increase—possible increases or decreases in runoff/river discharge, increased flow variability (32,44,45,46)
- Major expansion of northern Gulf of Mexico hypoxic zone possible—other impacts on coastal systems related to changes in precipitation/nonpoint-source pollutant loading (45,47)
- Changes in estuary systems and wetland extent, biotic processes, species distribution (44,48)

Figure 15-1: Potential water resources impacts.

al., 1996). Rivers that originate in mountainous regions will be particularly sensitive to winter precipitation in the headwaters, regardless of conditions in the downstream semi-arid zone (e.g., Cohen, 1991). In addition, "…severe flood events may be more damaging in drier climates where soils are more erodible…" (Arnell *et al.*, 1996).

Little research attention has been given to the possible impacts of climate change on sediment transport and deposition, which could affect aquatic ecosystems, reservoir storage capacity, potential flood damages, and the need for dredging operations. However, projected increases in the intensity of precipitation events could contribute to increased erosion and sedimentation in some areas (Mount, 1995).

15.2.1.1. Impacts and Adaptation Options

The impacts of hydrological changes and options for effective adaptation will depend on the nature of the hydrological changes, the amount of buffering provided by natural and artificial storage capacity, the nature of demands on the resource, and the effectiveness with which institutions in place balance competing demands. Continued increases in demand are likely for the multiple services provided by North American water resources, encompassing out-of-stream and instream uses. Adaptations to the effects of climate change therefore will occur in conjunction with adjustments to changes in the level and characteristics of water demands.

A major comparative study of six U.S. water resource systems found that although climate change could have significant and often adverse impacts on system performance, adjustments to reservoir operations could be made, allowing those impacts to be smaller than the underlying hydrological changes (Lettenmaier *et al.*, 1999). The authors also found that "The effects of anticipated demand growth and other plausible future operational considerations…would about equal or exceed the effects of climate change over system planning horizons" (Lettenmaier, *et al*., 1999).

The importance of future changes in demand is echoed by Frederick and Schwarz (1999). They found that even in the absence of climate change, the annual cost of supplying water to meet projected increases in U.S. water demands would be about US$13.8 billion higher in 2030 than in 1995, based on the current trend of increasingly using conservation to balance growing demands with supplies. This trend has been driven by "…the high costs of developing new supplies, environmental concerns, a growing appreciation for the values of instream flows and efforts to improve water quality" (Frederick and Schwarz, 1999). Using projected runoff changes calculated by Wolock and McCabe (2000) for 18 water resource regions, the study found that runoff increases projected by the HadCM2 model tended to reduce the cost of balancing future water supplies and demands, whereas the reduced flows projected by the CCC model resulted in large cost increases. With the CCC model projections, the study found that under an "efficient management" scenario, annual water costs could increase "…by nearly US$105 billion, about US$308 per person. Much higher cost increases would result from policies to maintain relatively high streamflow levels under such dry conditions" (Frederick and Schwarz, 1999).

This finding—that institutions can have significant impacts on the costs arising from reduced water availability—is supported by a study that assessed the possible consequences of a severe sustained drought on the Colorado River system (Lord *et al.*, 1995). The study authors found that the "Law of the River," as currently interpreted and implemented, would leave sensitive biological resources, hydropower generation, recreational values, and Upper Colorado basin water users vulnerable to damages despite extraordinary engineering attempts to drought-proof the river. The study also found that certain proposed institutional and system operating changes could considerably alter the level and incidence of the damages (Booker, 1995; Kenney, 1995; Lord *et al.*, 1995; Sangoyomi and Harding, 1995). For example, reallocation from low- to high-valued uses (e.g., through intrastate or interstate water marketing) and changes in reservoir storage policies to hold water in the Upper Colorado basin to reduce evaporative losses could reduce consumptive use damages by more than 90% (Booker, 1995).

Such "what if" analyses can foster creative thinking about adaptation options. Future adaptation strategies also are likely to build on current creative solutions to meeting water supply challenges. For example, when increases in agricultural and sewerage runoff in the Catskill/Delaware watershed region threatened the quality of New York City's water supplies, the city was faced with a choice of either building an artificial filtration plant or taking action to protect and restore the natural purification capacity of the watershed's ecosystem. The capital cost of the filtration plant would have been US$6–8 billion, plus annual operating costs of US$300 million. The city found that for a fraction of that cost it could enter into agreements with landowners in the watershed to adopt land-use practices

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≺ *Figure 15-1 Notes*

1. Loukas and Quick, 1999; **2.** Taylor and Taylor, 1997; **3.** Brugman *et al*., 1997; **4.** Hofmann *et al*., 1998; **5.** BESIS, 1999; **6.** Melack *et al*., 1997; **7.** Hamlet and Lettenmaier, 1999; **8.** Cohen *et al*., 2000; **9.** Wilby and Dettinger, 2000; **10.** Leung and Wigmosta, 1999; **11.** Wolock and McCabe, 2000; **12.** Felzer and Heard, 1999; **13.** Gleick and Chalecki, 1999; **14.** Thompson *et al*., 1998; **15.** Fyfe and Flato, 1999; **16.** McCabe and Wolock, 1999; **17.** Leith and Whitfield, 1998; **18.** Williams *et al*., 1996; **19.** Hauer *et al*., 1997; **20.** Wilby *et al*., 1999; **21.** USEPA, 1998b; **22.** Hurd *et al*., 1999; **23.** USEPA, 1998; **24.** Marsh and Lesack, 1996; **25.** Maxwell, 1997; **26.** Rouse *et al*., 1997; **27.** MacDonald *et al*., 1996; **28.** Herrington *et al*., 1997; **29.** Strzepek *et al*., 1999; **30.** Clair *et al*., 1998; **31.** Yulianti and Burn, 1998; **32.** Lettenmaier *et al*., 1999; **33.** Woodhouse and Overpeck, 1998; **34.** Evans and Prepas, 1996; **35.** Eheart *et al*., 1999; **36.** Hurd *et al*., 1998; **37.** Mortsch and Quinn, 1996; **38.** Chao, 1999; **39.** Magnuson *et al*., 1997; **40.** Moore *et al*., 1997; **41.** Abraham *et al*., 1997; **42.** Frederick and Gleick, 1999; **43.** Hare *et al*., 1997; **44.** Mulholland *et al*., 1997; **45.** Justic *et al*., 1996; **46.** Arnell, 1999; **47.** Cruise *et al*., 1999; **48.** Porter *et al*., 1996.

that would adequately protect water quality, making the filtration plant unnecessary (PCAST, 1998; Platt *et al.*, 2000).

Adjustments to the effects of climate change as well as to evolving demands for out-of-stream and instream water uses may entail impacts on the distribution of water-use benefits. The question of who will bear the costs of any reduction in water availability depends on the nature and ownership of existing water rights, how those rights are measured, and how they may be modified by other policies. In the United States, federal legislation—including the Endangered Species Act and the Clean Water Act—has regulated or constrained development of many new water projects and could be applied to modify existing water diversions (WWPRAC, 1998). Native American (aboriginal) communities often possess reserved water rights that, despite their high priority, have never been developed or clearly quantified. Substantial litigation and negotiation efforts have focused on clarifying these rights. Any significant change in water availability may heighten tensions between these communities and neighboring water users (Echohawk and Chambers, 1991). Under riparian water law and permit systems, governmental authorities may have substantial discretion in regulating water uses under drought conditions (Abrams, 1990; Flood, 1990; Sherk, 1990; Dellapenna, 1991; Scott and Coustalin, 1995). Under the prior appropriation system of water law, which is followed in western Canada and most states in the western portion of the United States, the risk of a shortfall generally is inversely proportional to the seniority of the right. Many junior rightholders, however, have access to water stored in reservoirs, which improves their security of supply.

Several studies have argued that improving the functioning of water markets could help to create the kind of flexibility needed to respond to uncertain changes in future water availability (e.g., Trelease, 1977; Tarlock, 1991; OTA, 1993; Miller *et al.*, 1997). If water supplies decline in particular locations or seasons, water markets could soften the impacts by moving water from lower to higher valued uses. In the western United States, where irrigation now accounts for more than 80% of consumptive water use, water market activity is likely to continue the current trend of movement of water out of irrigated agriculture to accommodate other water uses (WWPRAC, 1998). However, water markets are not likely to adequately protect instream flows and sensitive biological resources unless public agencies are given budgets to buy or rent water to protect those values (Wilkinson, 1989; NRC, 1992). In addition, water rights have to be clearly defined for water markets to function properly. Even in the western United States, where water markets have developed rapidly in recent years (Saliba and Bush, 1987; NRC, 1992; Colby, 1996; Yoskowitz, 1999), market development has been hampered by the fact that water rights often are not well documented (e.g., Costello and Kole, 1985; Gould, 1988; Colby, 1998). To avoid adverse impacts on other water users, water authorities typically review each transfer proposal. The entire process often entails substantial transaction costs, and these costs differ significantly across jurisdictions (Saliba and Bush, 1987; MacDonnell, 1990; NRC, 1992). This suggests that administrative practices and other institutional factors affect the efficiency of the water transfer process and that administrative reforms to reduce transaction costs could improve adaptability to the effects of climate change.

Finally, permanent water transfers are not particularly effective in promoting flexible adaptation to climatic variability or uncertain climate changes. Small, temporary transfers through water banks such as California's Emergency Drought Water Banks would provide greater flexibility (see Section 15.3.2.3).

Although well-functioning water markets may ameliorate the socioeconomic impacts of reduced water availability, they cannot completely eliminate the adverse impacts of a drying scenario. Using models that assume optimal allocation of water across all sectors (which implicitly assumes perfect, cost-free water markets), Hurd *et al*. (1998) estimated the water resources-related costs of climate change scenarios for four major river basins in the United States. They found that losses from moderate and severe drying scenarios tended to be greater in the semi-arid western United States than in the eastern states. From this analysis, they project that national water-related welfare losses arising from a temperature increase of 2.5°C coupled with a 7% increase in precipitation would be on the order of US$9.5 billion. A scenario with a temperature increase of 5°C coupled with no change in precipitation would result in losses of US$43 billion. Overall, they found that the economic costs probably would be dominated by impacts on water quality and instream nonconsumptive water uses, especially hydroelectricity generation. This result hinges on their assumption that irrigators—who currently dominate ownership of water in the western United States—would benefit by selling some of their water to other sectors. More realistic assumptions regarding the costs of transferring water through water markets would have produced larger estimated losses and a different distribution of losses across sectors.

Water rights are not always defined in terms that would permit the transfer of a specific amount of water from one use to another, particularly in eastern U.S. and Canadian jurisdictions that still follow a traditional riparian system of water law (Tarlock, 1989; Flood, 1990; Scott and Coustalin, 1995). In such areas, accommodation of competing demands and changing supplies will require local and regional planning and coordination. For example, if the levels and outflows of the Great Lakes–St. Lawrence system decline, as most available scenarios suggest, adaptation options are likely to raise sensitive interjurisdictional allocation issues and may require infrastructure investments that will increase the need for cooperative planning and management of the basin's water resources (Bruce *et al.*, 2000).

15.2.1.2. Water Quality

Water quality changes may be driven by changes in hydrological flowpaths in a watershed that are associated with changes in patterns of precipitation and evapotranspiration and changes in total flow in streams and rivers or in water level or duration of ice cover in temperate lakes. In regions such as the Precambrian shield, where watersheds are predicted to become drier in spring and summer, concentrations of dissolved organic material reaching lakes and streams from their catchments will decrease, increasing water clarity and changing physical and thermal regimes by increasing average thermocline depths in small, stratified lakes, for example (Snucins and Gunn, 1995; Schindler *et al.*, 1996; Perez-Fuentetaja *et al.*, 1999). In contrast, in the Great Lakes and other large lakes where dissolved organic carbon (DOC) concentrations are low, thermocline depths are determined by area or wind fetch and are not affected by DOC (Fee *et al.*, 1996). Models for the Great Lakes indicate that rapid spring warming may cause shallower and steeper thermoclines (reviewed by Magnuson *et al.*, 1997). For lakes and streams receiving flow from deep and shallow groundwater sources, drier watersheds could cause the major ion chemistry to be dominated more by the deep baseflow water sources (Webster *et al*., 1996).

In several regions where warmer temperatures and longer growing seasons are expected, changes in water quality will be driven by increases in primary production, organic matter decomposition, and nutrient cycling within lake or stream ecosystems (e.g., Mulholland *et al.*, 1997). In the Great Lakes region, warming over the past 60 years already has moved forward by an average of 3 weeks the time of ice-cover breakup (ice-out), which has moved ahead the spring bloom of algal growth and changed the seasonal dynamics of nutrient utilization and production and decomposition of organic matter (Magnuson *et al.*, 1997).

Where streamflows and lake levels decline, water quality deterioration is likely as concentrations of nutrients and contaminants from wastewater treatment, agricultural and urban runoff, and direct industrial discharge increase in reduced volumes of carrying waters. The extent of water quality deterioration will depend on adaptations in land use, population, and water use under changing climate. Warmer water temperatures may have further direct impacts on water quality—for example, by reducing dissolved oxygen concentrations. In the southeast, intensification of the summer temperature-dissolved oxygen squeeze (simultaneous high water temperatures and low dissolved oxygen concentrations) in many rivers and reservoirs is likely to cause a loss in habitat for coolwater fish species (Mulholland *et al.*, 1997).

Changes in the characteristics of precipitation events also may affect water quality, in complex ways. For example, increased incidence of heavy precipitation events as predicted for the southeast may result in increased leaching and sediment transport, causing greater sediment and nonpoint-source pollutant loadings to watercourses (Mulholland *et al.*, 1997). Because these high-flow events are episodic, the associated increase in nutrient and contaminant dilution during the event is not likely to offset the deleterious effects on water quality from low summer flows.

Warmer temperatures will increase the salinity of surface waters, especially lakes and reservoirs with high residence times, by increasing evaporative water losses. Higher initial salinities in reservoir water will then exacerbate salinity problems in irrigation return flow and degrade water quality in downstream habitats.

15.2.1.3. Flood Risks

Flooding poses risks to human life and property. Vulnerability to flood damages is highly location-specific, and there is considerable variability across watersheds in the value of developed property and population located within 500-year floodplains as defined by current understanding of current climate (Hurd *et al.*, 1999). Flood events also can have significant impacts on ecosystems. For example, heavy precipitation events may leach nitrogen and other nonpoint-source pollutants from agricultural lands, and the resulting nutrient pulse may severely stress coastal and estuarine ecosystems (Justic *et al.*, 1996; Rabalais *et al.*, 1996). In addition, the influx of freshwater during floods may affect estuary-dependent species. For example, oyster populations suffer severe declines when floods reduce the salinity of Galveston Bay (Hofmann and Powell, 1998).

Coupling of natural disasters, such as extreme storm events, with large-scale human disturbance of the landscape can cause extreme disturbance to freshwater and marine resources that would not be predicted by considering these effects independently. The consequences of Hurricanes Dennis and Floyd in eastern North Carolina in September 1999 provide a recent example of the importance of this coupling (see Section 15.3.2.7). Rainfall of almost 1 m generated highly polluted, organic-rich floodwaters as containment ponds for poultry and hog waste were breached and raw sewage, fertilizers, decaying vegetation, and other organic sources were entrained by the flood. One serious effect was contamination of shallow groundwater sources with fecal coliforms and organic pollutants, which may jeopardize local water supplies long after the floodwaters subsided. Of even greater economic impact for this region, the surge of floodwater caused the waters of the biologically rich estuary between the Carolina mainland and the Outer Banks to be the color of weak coffee and deposited large amounts of organic material in coastal sediments, especially in the estuaries and westernmost Pamlico Sound. The Albemarle-Pamlico Estuarine System provides fully half of the area used as nursery grounds for commercially important fish from Maine to Florida. These waters are a vitally important feeding area for small sport fish and menhaden and an important nursery for flounder, weakfish, shrimp, and crabs. At the time, there was considerable concern that the release of nutrients and consumption of oxygen as deposited organic material decomposed would cause physical stresses, disrupting the coastal food web and commercial fisheries for a significant period (Paerl *et al.*, 2000). As it turned out, the mesohaline estuaries west of the Pamlico Sound sustained the greatest damage from pollution that was washed in and deposited to the bottom muds (Burkholder *et al*., 2000). Pamlico Sound was protected from high impacts because much of the pollution settled out in the estuaries and because of its high flushing exchange with the ocean relative to the estuaries. The high dilution provided by the extreme runoff associated with Hurricane Floyd was a “saving grace” that appeared to buffer the pollution effects, so no fish kills were reported throughout the system (Burkholder *et al.*, 2000). However, concerns remain about chronic, more long-term impacts from the pollution that remained behind in the estuaries.

Possible changes in runoff patterns, coupled with apparent recent trends in societal vulnerability to floods in parts of North America, suggest that flood risks may increase as a result of anthropogenic climate change (see Section 15.2.5). Changes in snowpack accumulation and the timing of melt-off are likely to affect the seasonal distribution and characteristics of flood events in some areas. For example, in mountainous western watersheds, winter and early spring flood events may become more frequent (Melack *et al.*, 1997; Lettenmaier *et al.*, 1999). In southeastern Canadian and northeastern U.S. watersheds, reductions in winter snowpacks and river ice will tend to reduce winter and spring flood risks (Bruce *et al.*, 2000), where at present “rain-on-snow and snowmelt floods can be the largest and most destructive stormflow events in the region” (Platt *et al.*, 2000). However, Canadian rivers in northern areas may begin to experience winter ice break-ups and associated flooding (Bruce *et al.*, 2000).

In inflation-adjusted terms, average annual flood damage has increased in the United States over the past few decades. This increasing trend in damages appears to be related to increases in population and the value of developed property in floodplains, as well as changes in precipitation characteristics, with perhaps as much as 80% of the trend attributable to population and wealth changes (Pielke and Downton, 2000). Measured as a proportion of real tangible wealth, average annual flood damages have been roughly constant over time (Pielke and Downton, 2000). This ongoing vulnerability comes despite the fact that various federal, state, and local governments and private entities have built approximately 40,000 km of levees along the rivers and streams of the United States—a combined total distance that is long enough to encircle the Earth at the equator (Pielke, 1999).

Recent severe flood events—particularly the 1993 Mississippi River floods, the 1996 Saguenay flood, the 1997 Red River flood, and winter flooding in California in 1997—have led to reexaminations of traditional approaches to flood management. For example, a U.S. federal interagency task force was formed in the wake of the 1993 floods, and its recommendations have contributed to altered federal practices (IFMRC, 1994). In an assessment of the 1993 floods, which caused on the order of US$18 billion in damages, Changnon (1996) notes that the extreme and prolonged flooding had significant and unexpected impacts that defied previous experience and design extremes. Changnon further concludes that many systems for monitoring and predicting flood conditions were inadequate; that incomplete or incorrect information was released during the flood; and that many previous approaches to mitigate flood losses failed. He also identifies benefits, including benefits to the natural ecosystem of the Mississippi floodplain.

It has been demonstrated that the efforts of one community to protect itself from floods (for example, through levee construction) may affect the likelihood of flood damages in other communities (Mount, 1995). Therefore, coordinated regional planning and management may allow more efficient adaptation to changing flood risks than uncoordinated efforts by individual communities. However, there are many things that individual communities can do to rationally adapt to flood risks and reduce the likelihood of serious damages (City of Tulsa, 1994). Many entities that are responsible for floodplain management are rethinking the design of levee systems and other flood management policies (City of Tulsa, 1994; IFMRC, 1994; Mount, 1995; Tobin, 1995; Pielke, 1996; Wright, 1996). These developments may improve resilience to future flooding events, but it is not yet clear if recent policy discussions will lead to substantial and effective changes in floodplain management or flood response practices.

15.2.2. Natural Resources

In this section, impacts studies on forests, grasslands, and protected areas are reviewed. Protected areas include mountains, wetlands, and coastal/marine areas.

15.2.2.1. Forests

We must consider two types of climate change effects on forests:

- Changes in the functions of existing forests relating to productivity, nutrient cycling, water quality, ecosystem carbon storage, trace gas fluxes, and biodiversity.
- Changes in composition as forests regenerate under altered conditions. Fundamental changes in forest ecosystem structure can lead to very dramatic changes in functions. Climate change effects on catastrophic events (e.g., fire, insect outbreaks, pathogens, storms) that have marked effects on ecosystem structure are particularly important to consider.

A general discussion of forest response to climate change appears in Chapter 5.

North America contains about 17% of the world’s forests (Brooks, 1993), and these forests contain about 14–17% of the world’s terrestrial biospheric carbon (Heath *et al.*, 1993). Key climate change issues related to forests in North America include:

- Changes in the geographic range of different forest types
- Increases in the frequency of fire and insect outbreaks
- Changes in the carbon storage function of forests (i.e., from sinks to sources)
- Evaluation of the importance of multiple stresses (ozone, nitrogen deposition, land-use change) that work in concert with climate change

- Changes in human interactions with forests (e.g., risk to settlements, recreational use)
- Concern for the boreal forests of Canada because of their large extent, carbon reserves, and commercial value, combined with the fact that climate change is expected to be most severe at high latitudes.

15.2.2.1.1. Changes in function of existing forests

There is strong evidence that there has been significant warming at high latitudes (Jacoby *et al.*, 1996) and that this warming has increased boreal forest productivity (Ciais *et al.*, 1995; Myneni *et al.*, 1997). However, carbon balance is not necessarily changed by increases in productivity. Net ecosystem carbon flux (or carbon storage) is a product of changes in ecosystem production and decomposition. Keyser *et al.* (2000) used long-term meteorological records to drive the BIOME-BGC model to evaluate changes in the carbon balance of North American high-latitude forests. They conclude that increases in net primary production and decomposition were roughly balanced and that net ecosystem production (i.e., total carbon storage) was not likely to shift significantly with climate change. In contrast, Goulden *et al.* (1998) and Lindroth *et al.* (1998) found that boreal forests could become net CO_2 sources. The key uncertainties in this area are the effects of permafrost melting on release of previously frozen carbon, the ability of more productive ecosystem types (aspen, white spruce) to expand in extent, and the importance of soil moisture. Evaluating changes in carbon balance in northern forests should be a priority topic for research.

There is consensus emerging that at mid-latitudes, site-specific conditions as well as history, human management, air pollution, and biotic effects (e.g., herbivory) are much stronger controllers of forest productivity, decomposition, and carbon balance than climate change or CO_2 enrichment (Eamus and Jarvis, 1989; Aber and Driscoll, 1997; Ollinger *et al.*, 1997; Goodale *et al.*, 1998; Stohlgren *et al.*, 1998).

There is general agreement that excess nitrogen deposition, which is most pronounced in the mid-latitudes, has increased carbon storage in mid-latitude forests by facilitating increases in production in response to elevated CO_2 (Townsend *et al.*, 1996). The ability of forests to continue to absorb excess nitrogen and CO_2 is not at all certain, however (Norby, 1998).

Evidence for climate change effects on forest ecosystem "services" (i.e., functions that are important to productivity, environmental quality, and other human concerns) are beginning to emerge in North America. Murdoch *et al.* (1998) suggest that climate warming increases soil acidification and stream nitrate (NO_3^-) concentrations, especially in forests with a history of high nitrogen deposition. Extreme climate events (e.g., soil freezing, which may increase as a result of warming-induced decreases in snow cover) also appear to lead to increases in soil and stream acidification and NO_3^- levels (Mitchell *et al.*, 1996; Groffman *et al.*, 1999). Evaluations of climate change effects on fluxes of trace gases other than CO_2 [methane (CH_4), nitrous oxide (N_2O)] have been inconclusive (Prather *et al.*, 1995).

Climate change effects on biogeochemical processes are likely to be small relative to site characteristics, land-use history, and atmospheric chemistry, especially in mid-latitudes (Aber and Driscoll, 1997).

15.2.2.1.2. Wholesale changes in forest structure and function

If climate change results in wholesale replacement of one forest community with another, effects on ecosystem functions ranging from carbon storage to wildlife habitat could be dramatic (Tilman, 1998). Possible wholesale changes in forest structure have been a great source of uncertainty and concern. The North America assessment in the IPCC's *Special Report on Regional Impacts of Climate Change* concluded that there were equal probabilities of considerable forest dieback and enhanced forest growth, given state-of-the-art models and GCM predictions (Shriner and Street, 1998).

Many types of models (biogeographic individual-based forest growth, gap, dynamic global vegetation, regression tree analysis, response surface, richness, and rare and endangered species) have been used with numerous climate scenarios to examine broad-scale climate change-induced changes in vegetation (VEMAP Members, 1995; Shugart and Smith, 1996; Aber *et al.*, 2001). There is great uncertainty about the precision and accuracy of each of these models and the assumptions that underlie them (Loehle and LeBlanc, 1996; Repo *et al.*, 1996; Beuker *et al.*, 1998). Many studies suggest that all major forest types in North America will expand northward and most will increase in extent in the next 50–100 years. The increase in forests is predicted to be driven by slight warming coupled with increases in water-use efficiency (WUE) associated with increased atmospheric CO_2 (Saxe *et al.*, 1998). However, with continued warming, increased water use associated with higher temperatures overwhelms the CO_2 effect, resulting in potentially important decreases in forest area (Aber *et al.*, 2001).

Wholesale changes in forest ecosystem structure over time are likely to be mediated by changes in disturbance regimes and/or catastrophic events that provide opportunities for forest regeneration over large areas (Suffling, 1995; Loehle and LeBlanc, 1996). Of particular interest in North America are changes in fire and insect outbreaks.

15.2.2.1.3. Fire

Stocks *et al.* (1998) used outputs from four GCMs to project forest fire danger levels in Canada under a warmer climate. Their analysis shows an earlier start to the fire season and significant increases in the area experiencing high to extreme fire danger. Increased lightning frequency associated with global warming also may increase fire frequency (Goldammer and Price, 1998). Changes in fire frequency have a wide range of effects, from production of tropospheric aerosols that influence climate (Clark *et al.*, 1996) to changes in ecosystem carbon storage and trace gas fluxes. The long-term effects of fire will depend heavily on changes in human fire management activities, which are uncertain—especially in remote boreal forests, where fire is a critical issue (e.g., see Section 15.3.2.8). In mid-latitudes, climate effects on fire frequency are much less important than human management factors (Veblen *et al.*, 2000).

15.2.2.1.4. Insects

Insects represent dominating disturbance factors (Hall and Moody, 1994) in North America's forests; during outbreaks, trees often are killed over vast areas (Hardy *et al.*, 1986; Candau *et al.*, 1998). Because the potential for wildfire often increases in stands after insect attack (Stocks, 1987; Wein, 1990), uncertainties in future insect damage patterns also lead to uncertainties in fire regimes. Insect outbreaks also lead to changes in ecosystem carbon and nutrient cycling, biomass decomposition, energy flow (Mattson and Addy, 1975; Schowalter *et al.*, 1986; Szujecki, 1987; Haukioja *et al.*, 1988; Chapin, 1993; Haack and Byler, 1993), and competitive relationships between plants (Morris, 1963; Holling, 1992)—hence successional pathways, species composition, and forest distribution.

Climate change already appears to be accelerating the seasonal development of some insects (Fleming and Tatchell, 1994). Forecasts based on historical relationships between outbreak patterns and climate in specific areas are likely to predict change as the climate in those areas changes. Such analyses suggest more frequent [mountain pine beetle (Thomson and Shrimpton, 1984), spruce budworm (Mattson and Haack, 1987), eastern hemlock looper (Carroll *et al.*, 1995), jack pine budworm (Volney and McCullough, 1994), western spruce budworm (Thomson *et al.*, 1984)] or longer [forest tent caterpillar (Roland *et al.*, 1998), spruce budworm (Cerezke and Volney, 1995)] outbreaks or range shifts northward and to higher elevations [spruce budworm (Williams and Liebhold, 1997)] as climate change progresses.

15.2.2.1.5. Vegetation In human settlements

Vegetation in human settlements plays two potentially important roles that are relevant to climate change: modification of local climate and sequestration of carbon.

Trees reduce demands for seasonal heating and cooling of the interiors of buildings and absorb air pollutants (Heisler, 1986; Nowak *et al.*, 1994). In the city of Chicago, calculations suggest that increasing tree cover by 10% could reduce building energy use by 5–10% (Nowak *et al.*, 1994). Thus, urban tree planting represents an adaptive strategy that can reduce energy use and associated CO_2 emissions and counteract temperature increases in urban areas, which are predicted to be extreme in some cases.

Carbon density in residential areas can be significant, amenable to management, and often overlooked in evaluation of landscape, regional, and national carbon budgets. Freedman *et al.* (1996) found that aboveground tree biomass of an old residential neighborhood in Halifax, Nova Scotia, was only slightly smaller than that of a natural forest in a nearby reserve. Nowak *et al.* (1994) estimated that carbon storage by urban forests in the United States was 440–990 Mt. There is a strong need for better estimates of "natural" carbon fluxes in human-dominated environments.

15.2.2.2. Protected Areas

15.2.2.2.1. Mountains

In the 20th century, there has been increasing human pressure on mountainous regions, initially through trapping, forestry, and reservoir construction and now through development of ski areas and other resorts and construction of residences, as well as forestry and continuing reservoir construction in northern Canada. At the same time, however, the national park systems in the United States and Canada and wilderness preserves have expanded to include many mountainous areas that are essentially pristine with respect to human development, especially in the Rocky Mountains. It is now recognized that these protected mountain ecosystems are still vulnerable to anthropogenic change through transport of atmospheric contaminants, such as nitrate and sulfate in acid rain, and through climate change. Warming of the climate eventually will cause two major changes—retreat of mountain glaciers and upward movement of treeline—and the response times for reaching new equilibrium conditions are on the order of 100 years or more, so these responses will lag continuing climate change.

Retreat of glaciers is driven by the rate of ablation, which includes melt, exceeding the rate of advance driven by snow accumulation over the glacier, and corresponds to a change in the shape of the glacier to a new equilibrium. Retreat of mountain glaciers already has begun in North America (Brugman *et al.*, 1997) and in other regions of the world, and this retreat will contribute to sea-level rise in an amount comparable in magnitude to expansion of ocean waters as a result of warming. On a regional scale, the retreat of glaciers will affect water resources by changing (probably decreasing) water supply from glacial melt during summer or changing the spatial location of the melt source [summer flows initially may increase but eventually will decline as glacier reservoir capacity declines (Pelto, 1993)]. Furthermore, glacial retreat will expose terrain that gradually will evolve with soil development and revegetation, and new lakes will form in exposed basins. These changes eventually will influence the water quality of drainage from these lakes. These sequences of glacial advance and retreat have occurred through the quaternary; the effect of climate change is to induce these changes. In terms of human vulnerability to climate change, retreat of mountain glaciers also is significant because it is an observable change that can be directly comprehended by the public as an indicator of warming—more so than warming of the open ocean or an increase in extreme hydrological events. For example, a recent article in a travel magazine (*Conde Nast*) outlined vacations to view retreating glaciers in North America, Europe, and Africa while they were still there.

From paleolimnological studies of alpine and subalpine lakes, the rise in treeline in response to past warming of climate is well-documented. The boundary between alpine tundra and subalpine forest is controlled by extremes of temperature, moisture, and wind. Vegetation in both ecosystems is long-lived, and changes will proceed slowly and in a manner that depends on whether total annual snowpack decreases or increases and whether melt occurs earlier; both factors control the growth of alpine and subalpine species. Movement of treeline could have a minor feedback on climate change by sequestering more carbon in subalpine forests. The eventual effect of upward movement of the treeline will be to shrink the extent of alpine tundra in North America, possibly causing species loss and ecosystem degradation through greater fragmentation (see Section 15.2.6. and Chapter 5).

15.2.2.2.2. Wetlands

Wetlands represent a variety of shallow water and upland water environments that are characterized by hydric soils and plant and animal species that are adapted to life in saturated conditions (NRC, 1995). These ecosystems are considered to be of great importance in a variety of functional contexts, including waterfowl habitat, carbon sequestration, CH_4 production, flood regulation, pollutant removal, and fish and shellfish propagation (Mitsch and Gosselink, 1993). About 14% of Canada's surface area is covered by wetlands, which is 24% of the global total (NWWG, 1988). Approximately 6% of the United States is wetland (Kusler *et al.*, 1999).

Mid-latitude wetlands have been greatly affected by a variety of human activities over the past 200 years. More than 50% of the original wetlands in the United States have been destroyed for agriculture, impoundment, road building, and other activities (Dahl, 1990). Most of the remaining wetlands have been altered by harvest, grazing, pollution, hydrological changes, and invasion by exotic species (Kusler *et al.*, 1999). High-latitude wetlands have experienced much lower levels of human disturbance (Schindler, 1998).

Climate change can have significant impacts on wetland structure and function, primarily through alterations in hydrology, especially water-table level (Clair *et al*., 1998; Clair and Ehrman, 1998). Wetland flora and fauna respond very dynamically to small changes in water-table levels (Poiani *et al.*, 1996; Schindler, 1998). Moreover, climate change can exacerbate other stresses (e.g., pollution), especially in fragmented landscapes where wetlands have been cut off from other wetlands by a variety of landscape-level alterations (Mortsch, 1998; Kusler *et al.*, 1999). With rising sea levels, shoreline development and efforts to protect private property from coastal erosion could lead to loss of public tidelands and coastal marshes, particularly along bayshores where preservation of natural shorelines has received less policy attention than is the case for most ocean beaches (Titus, 1998).

Specific changes predicted to occur in North American wetlands are wide ranging. Sea-level rise will result in loss of coastal wetlands in many areas, with potentially important effects on ocean fisheries (Michener *et al*., 1997; Turner, 1997). Increased drought conditions in the Prairie Pothole Region of the northern Great Plains, which are forecast to occur under nearly all GCM scenarios, will significantly reduce U.S. breeding duck populations (Sorenson *et al.*, 1998). Tourism may benefit from extended seasons but will suffer if key processes (e.g., hunting, birding) are disrupted (Wall, 1998a). Alteration of water-table levels could affect the carbon sequestration function of the vast northern wetlands of Canada, but there is great uncertainty about the nature and extent of this effect (Moore *et al.*, 1998; Waddington *et al.*, 1998).

Wetlands have been the target of numerous protection and restoration efforts (NRC, 1995), which suggests that there is high potential for adaptive management in response to climate change, at least in mid-latitudes. Kusler *et al.* (1999) recommend a series of strategies for reducing the impacts of climate change on wetlands. These strategies include better control of filling and draining of wetlands, prevention of additional stresses, prevention of additional fragmentation, creation of upland buffers, control of exotic species, protection of low flows and residual water, enhanced efforts to restore and create wetlands, and aggressive efforts in stocking and captive breeding of critical wetland species. Five states in the United States have adopted rolling easement policies, which ensure that wetlands and/or beaches can migrate inland as sea level rises, instead of being squeezed between coastal development and the advancing sea (Titus, 1998). These efforts would be greatly enhanced by creation of regional inventories and management plans for wetlands at greatest risk from climate change.

15.2.2.2.3. Coastal/Marine

With the concentration of population on the coasts, various development constraints and environmental regulations have been enacted to protect areas of coast as wildlife preserves and for harvesting of shellfish. Coastal ecosystems clearly are vulnerable to change associated with eventual sea-level rise (see Section 15.2.2.3.4). Coastal and marine biota also are vulnerable to changes in upwelling, current dynamics, freshwater inflow, salinity, water temperatures, and other processes that affect food webs and nursery areas (Boesch *et al*., 2000). Moreover, long-term studies of estuaries such as San Francisco Bay have indicated that natural cycles of ecosystem processes, such as phytoplankton blooms, are being altered on a global scale by human activities. This includes manipulation of river flows, input of toxic contaminants and nutrients, and invasion of exotic species (Cloern, 1996). Thus, in the nearer term, estuaries and coastal ecosystems may be most vulnerable to hydrological changes in rivers and groundwater flows from shifts in inland precipitation, evapotranspiration, and river ecosystem dynamics.

The increased frequency and geographical range of incidents of hazardous blooms in estuaries on the Gulf, Atlantic, and Pacific coasts has caused serious economic impacts for numerous fisheries and poses a great public health challenge in closing beaches to shellfish. Consumption of toxic algae by shellfish causes the shellfish to contain concentrations of toxins that are high enough to cause paralysis and death of humans who consume the shellfish. This situation has raised concerns that increased nitrogen loading to watersheds has led not only to general coastal eutrophication but also to a greater probability of circumstances that are conducive to these blooms. Factors that appear to contribute to harmful algal bloom occurrence are warmer temperatures and high runoff from watersheds that feed the estuaries, although much remains to be learned and predictive capability has yet to be achieved. Thus, indirect effects of climate change, which exacerbate the hazardous algal bloom problem, could be significant and difficult to identify until better understanding is gained (Anderson, 1997; see Chapter 6).

15.2.2.2.4. Wildlife

The Endangered Species Act in the United States and other regulatory efforts preserve and manage wildlife populations in many regions of North America. These efforts have begun to involve habitat protection and ecosystem management rather than taking a strict population focus. Changes in habitats driven by climate change could further restrict wildlife populations. One process would be causing habitats to be less interconnected, restricting migration of individuals among different populations and causing loss of genetic diversity within more isolated populations. This process is a concern for aquatic and terrestrial wildlife.

Fish populations and other aquatic resources are likely to be affected by warmer water temperatures, changes in seasonal flow regimes, total flows, lake levels, and water quality. These changes will affect the health of aquatic ecosystems, with impacts on productivity, species diversity, and species distribution (Arnell *et al.*, 1996). For example, warming of lakes and deepening of thermoclines will cause a loss of habitat for coldwater fish in areas such as Wisconsin and Minnesota, and decreases in summer flow and increased temperatures will cause loss and fractionation of riverine habitat for coolwater fish species in the Rocky Mountain region (Rahel *et al.*, 1996; Cushing, 1997).

Wetlands and dependent wildlife resources may be adversely affected by general increases in evapotranspiration and reduced summer soil moisture, which may reduce the extent of semi-permanent and seasonal wetlands, particularly in the prairie regions of North America (Poiani *et al.*, 1995).

The state of terrestrial wildlife in North America varies geographically, by taxa, and by habitat association. In general, biodiversity increases from north to south, and species that are associated with rare habitats are most likely to be at high risk of extinction (Dobson *et al.*, 1997; Ricketts *et al.*, 1999). Many factors can cause a species to be at risk of extinction, but the most common causes include loss of habitat, pressures from introduced species or hunting, and reduced fitness as a result of chemical contaminants (Wilson, 1992; Meffe and Carroll, 1994). A minimum estimate of the number of species at risk comes from data for the United States, for which a recent summary suggests that 42 mammal species, 56 bird species, 28 reptile species, and 25 amphibian species are considered at least vulnerable to extinction (UNEP, 2000). Key additional pressures on wildlife associated with global climate change include changes in temperature and precipitation, changes in sea level, and changes in the frequency of extreme weather events (Peters, 1992; Parmesan *et al.*, 2000).

Climate-related pressures can act directly on wildlife through physiological effects (i.e., changes in growth rates, food demands, abilities to reproduce and survive) or indirectly through effects on other plant and animal species (e.g., Payette, 1987; Lewis, 1993; Post and Stenseth, 1999). These physiological effects can lead to changes in the range and abundance of North American species; recent studies suggest that we already are seeing climate-linked changes in butterflies (Parmesan, 1996) and desert-associated species (Brown *et al.*, 1997b; Smith *et al.*, 1998a). A key potential indirect effect of climate change on wildlife is loss of total habitat available as a result of changes in the distribution of a particular habitat type. An obvious example is loss of coastal habitat as a result of sea-level rise; in many places, coastal habitats will not be able to shift inland because adjacent lands already are developed (Harris and Cropper Jr., 1992; Daniels *et al.*, 1993). Similarly, potential shifts in the ranges of species in northern habitats are bounded by the Arctic Ocean (Kerr and Packer, 1998). Asecond key impact of climate-change related pressures on wildlife relate to how species interact with other species on which they depend. Because temperature and precipitation can be triggers for many wildlife behaviors, changes in these factors may differentially impact species in the same location. We already have evidence that the timing of bird migrations (Bradley *et al.*, 1999; Inouye *et al.*, 1999), bird breeding (Brown and Li, 1996; Brown *et al.*, 1999; Dunn and Winkler, 1999), and emergence of hibernating mammals (Inouye *et al.*, 1999) is becoming earlier. Depending on how food sources and other related species respond to changes, wildlife may become decoupled from the many ecological relationships of which they are a part.

15.2.3. Food and Fiber

This section includes a review of impacts on agriculture, production forestry, and marine fisheries.

15.2.3.1. Agriculture

Most global climate change scenarios indicate that higher latitudes in North America would undergo warming that would affect the growing season in this region. For example, estimates of increases in the frost-free season under climatic change range from a minimum of 1 week to a maximum of 9 weeks (Brklacich *et al.*, 1997a). For the Prairies, Ontario, and Quebec, most estimates suggest an extension of 3–5 weeks. Estimated temperature increases for the frost-free season in Ontario and Quebec are mostly between 1.5 and 5.0°C, and agricultural moisture regimes show an even broader range of estimates, indicating precipitation changes for the Prairies and Peace River regions ranging from decreases of 30% to increases of 80% (Brklacich *et al.*, 1997a).

Although warmer spring and summer temperatures might be beneficial to crop production in northern latitudes, they may adversely affect crop maturity in regions where summer temperature and water stress limit production (Rosenzweig and Tubiello, 1997). Predicted shifts in thermal regimes indicate a significant increase in potential evapotranspiration, implying increased seasonal moisture deficits. Modeling studies addressing the southeast United States have shown that changes in thermal regimes under conditions of doubled CO_2 would induce greater demand for irrigation water and lower energy efficiency of production (Peart *et al.*, 1995).

15.2.3.1.1. Change in land use

Drought may increase in the southern Prairies, and production areas may shift northward in Canada. In assessing the potential for expansion to areas in northern Canada (i.e., north of 55°N and west of 110°W) and Alaska, Mills (1994) identified 57 Mha of potentially arable land (class 1-5, based on Canada Land Inventory criteria) with agricultural potential for use in either annual cropping or perennial forage systems. This estimate drops to 39 Mha when climatic limitations are imposed but under a scenario of doubled atmospheric CO_2, increases to 55 Mha with an accompanying improvement of land class to class 3. Similar outcomes—expansion of agricultural land, especially expansion of the zone suitable for corn and soybean production—are expected for northern areas of eastern Canada (Brklacich *et al.*, 1997a). Other case studies conducted in the southern portion of the Mackenzie basin in northwestern Canada show that two different climate-change scenarios would relax the constraints imposed by a short and cool frost-free season but that drier conditions and accelerated crop development would offset the potential gains of a warmer climate (Brklacich *et al.*, 1996, 1997b).

Southern regions growing heat-tolerant crops such as citrus fruit and cotton might benefit from reduced incidence of killing frosts resulting from a change in climate (Miller and Downton, 1993; Mearns *et al.*, 2000). Results of simulations without CO_2-induced yield improvement indicate that production of citrus fruit would shift northward in the southern United States, but yields may decline in southern Florida and Texas because of excessive heat during the winter (Rosenzweig *et al.*, 1996).

Mexican agriculture appears to be particularly vulnerable to climate-induced changes in precipitation because most (about 85%) of its agricultural land is classified as arid or semi-arid. Recent national assessments of the impacts of climate change indicate that the northern and central regions of Mexico are most vulnerable in the agricultural sector (Conde, 1999) and that in these regions, the area of land that is unsuitable for rainfed maize production would expand under climate change (Conde *et al.*, 1997). On average, more than 90% of losses in Mexican agriculture are caused by drought (Appendini and Liverman, 1995). Using five GCM-based scenarios, it was estimated that potential evaporation may increase by 7–16% and the annual soil moisture deficit could increase by 18–45% in important maize-growing regions in eastern Mexico (Liverman and O'Brien, 1991). Rising levels of CO_2 can have the greatest relative beneficial impacts when water is limited. Therefore, rising CO_2 may be expected to have a significant positive impact because so much of Mexican crops are water-limited and rising CO_2 enhances water-use efficiency (see Chapter 14).

15.2.3.1.2. Crop yields and adaptation

Depending on existing conditions, global warming and CO_2 enrichment can have positive or negative effects on crop yields. It is believed that yield increases in mid- and high latitudes are caused by positive physiological effects of CO_2, longer growing season, and amelioration of the effects of cold temperature on growth. Decreases in yield could result from shortening of the growing period, reduced water availability, and/or poor vernalization.

Estimates of the impacts of climate change on crops across North America vary widely (see Table 15-3). In some studies, the impacts range from nearly total crop failure for wheat and soybeans at one U.S. site to wheat yield increases of 180–230% for other sites in the United States and Canada (Brklacich *et al.*, 1994; Rosenzweig *et al.*, 1994). Recent modeling efforts indicate that the impacts on yields for many crops grown under dryland conditions, even without adaptation, is positive (Reilly *et al.*, 2000). Threshold limits associated with temperature increases may be important. Rosenzweig *et al.* (1995) report generally positive crop yield responses to temperature increases of 2°C, but yield reductions occurred at increases of more than 4°C. Modeled yield results that include the direct physiological effects of CO_2 are substantially different from those that do not account for such effects (Fischer *et al.*, 1996).

Although it is known that the distribution and proliferation of weeds, crop diseases, and insects are determined to a large extent by climate, most crop modeling efforts have not thoroughly accounted for potential impacts of climate change and variability on pest populations and ranges. Interactions between crops and pests under changing climate conditions will be very complex and are difficult to predict because elevated CO_2, warmer temperatures, and increased climate variability would alter the relationships between crops, weeds, and insects significantly. Higher temperatures and warmer winters could reduce winterkill of insects as well as broaden the range of other temperature-sensitive pathogens (Rosenzweig *et al.*, 2000). Increases in the

***Table 15-3**: Range of climate change scenario impacts on agriculture.*

Crop Yield (% change from current)		**Cropped Area**	**Change in Soil Carbon/Soil Quality**	**Pesticide Expenditures[6] (% change)**	**Irrigated Acreage**	**Livestock Production**
Canada[1]		Increase[3] and decrease[4]	Increase[5]	Corn +10 to +20 Wheat -15 to +15 Potato + 5 to +15 Soybean and Cotton +2 to +5	Increase[7]	Decrease[8]
– Smallgrains	-24 to +14[a] -35 to +66[b] -75 to +73[c] -17 to 0[d] +21 to +124[e]					
US[2]						
– Spring Wheat	+17 to +23					
– Winter Wheat	-9 to +24					
– Corn	+11 to +20					
– Soybean	+7 to +49					
– Sorghum	+32 to +43					
– Potato	+7 to +8					
– Citrus (oranges/grapefruit)	+13 to +40					

[1] Data pertain to (a) Peace River/agricultural margin; (b) Alberta, Saskatchewan, Manitoba; (c) Ontario, Quebec; and (d) Atlantic region [adapted from Brklacich *et al*., 1997a; based on scenarios from pre-1995 versions of four GCMs (CCC, GFDL, GISS, and UKMO) with different crop models (FAO and CERES), assuming no adaptation and no CO_2 fertilizer effects]. Data for note (e) represents yields of corn, spring and winter wheat, and canola [from McGinn *et al*., 1999; based on CCC model (results also show growing degree days increase by 50%)].

[2] Weighted average yield impact for crops grown under dryland conditions with adaptation, percentage change from base conditions (Reilly *et al*., 2000). Results based on simulations at 46 sites of current major production representing changes in climate predicted by the CCC, Hadley Centre, and Pacific Northwest National Laboratory models, and calculated using 20-yr averages centered around the year 2030, with an atmospheric CO_2 concentration of 445 ppm; crop yields were simulated by the DSSAT models (Tsuji *et al*., 1994).

[3] For Alaska and northwestern Canada (Mills, 1994), and Peace River region, northern Ontario, and Quebec in northern Canada (Brklacich *et al*., 1997b).

[4] For example, in citrus production in the southeastern United States, if risk of freeze damage increases with climate change (Miller and Downtown, 1993), area in cropland decreased 5–10% (Reilly *et al*., 2000).

[5] If soil conservation practices (e.g., no tillage, increased forage production, higher cropping frequency) implemented as mitigation strategies (TAR WGIII).

[6] Reilly *et al*. (2000) results based on simulations at 45 sites of current major production representing changes in climate predicted by the CCCM and Hadley Centre models, and calculated using 20-yr averages centered around 2090, with an atmospheric CO_2 concentration of 660 ppm.

[7] Irrigated acreage estimated to increase by 0.8–7.3Mha in the United States (Adams *et al*., 1990).

[8] Direct effects include warmer temperatures, which are estimated to suppress livestock appetite. If quality or supply of forage/feed grains is altered, production may be more affected by changes in pasture and grain prices (Adams *et al*., 1999).

incidence of extreme weather events could reduce the efficacy of pesticide applications and result in more injury to nontarget organisms (Patterson *et al.*, 1999).

Modeling studies of changes in crop production show strong regional effects, with some areas suffering significant losses compared to other regions—suggesting that climate change may affect the comparative advantage of agricultural production regions within North America. For example, in scenarios investigated for the U.S. National Assessment (Reilly *et al.*, 2000), the lake states, mountain states, and Pacific region showed gains in production, whereas the southeast, delta, southern Plains, and Appalachia generally lost. The economic impact of these changes in crop production as a result of climate change is considered to be mostly beneficial to society as a whole. The effects are largely detrimental to producers because the overall positive effect on production leads to decreasing prices. Thus, climate change is beneficial for foreign trade surplus and for consumers. Analyses of the economic effects of various climate change scenarios on the welfare of consumers and producers in the United States show that agricultural welfare strictly increases with 1.5 °C warming, but further warming reduces the benefit at an increasing rate (Mendelsohn *et al.*, 1999). Additional precipitation is strictly beneficial (Adams *et al.*, 1999).

The costs and benefits of climate change must be evaluated concurrently with behavioral, economic, and institutional adjustments brought about by climate change. These adjustments occur at different levels. For example, farm-level adaptations can be made in plant and harvest dates, crop rotations, selections of crops and crop varieties for cultivation, water consumption for irrigation, use of fertilizers, and tillage practices. At the market level, prices are a strong signal to adapt as farmers make decisions about land use and which crops to grow.

Current economic studies of climate change that include farm- and/or market-level adjustments suggest that the negative effects of climate change on agriculture probably have been overestimated by studies that do not account for adjustments that will be made. This may be caused by the ability of the agricultural production community to respond with great flexibility to a gradually changing climate. Typically, extreme weather poses a significant challenge to individual farming operations that may lack the spatial diversity and financial resources of large, integrated, corporate enterprises with production capabilities in one or more areas.

Simulation modeling using four GCM-based scenarios showed that U.S. cereal production decreases by 21–38% when farmers continue to do what they are now doing (i.e., no adaptation) (see Table 15-4). When scenarios that involve adaptation by farmers are used, decreases in cereal production are not as large and the adaptations are shown to offset the initial climate-induced reduction by 35–60% (Schimmelpfennig *et al.*, 1996; Segerson and Dixon, 1999).

15.2.3.1.3. Response to climate variability and extreme events

The effects of changes in the variability of temperatures and precipitation on crop yields have been evaluated through simulation modeling. Changes in diurnal and interannual variability of temperature and moisture can result in substantial changes in the mean and variability of wheat yields. In Kansas, doubling of temperature variability resulted in greatly reduced average yield and increased variability of yield, primarily as a result of crop failure by winterkill (Mearns *et al.*, 1996). The main risk of climate change to some regions may be primarily from the potential for increased variability. Increased variability of temperature and precipitation results in substantially lower mean simulated yields, whereas decreased variability produces only small increases in yield that were insignificant (Reilly *et al.*, 2000). This asymmetric response to temperature variability underscores a major reason that the corn belt region of the United States is so productive: There generally is low variability in temperature across the region. It should be noted, therefore, that if minimum temperatures increase more than maximums, two outcomes could be suggested: Temperature variability may decline, and winterkill should be reduced.

These effects of diurnal and interannual climate variation may have important implications for farm values. Economic analysis has shown that greater interannual variation is harmful to farm values, and the marginal effect of temperature variation is relatively larger than the effect of variations in precipitation (Mendelsohn *et al.*, 1999).

15.2.3.1.4. Vulnerability of livestock

The effects of climate change on livestock can be direct (e.g., effects of higher temperature on livestock appetite) or indirect (e.g., effects of changes in quantity and quality of forage from grasslands and supplies of feed). In areas where livestock rely on surface water availability, water quality could have an impact on weight gain. This would be particularly important where fewer water sources become used by greater numbers of cattle.

Table 15-4*: Percentage change in U.S. supply of cereals under various constraints, by climate change scenario (Schimmelpfennig et al., 1996).*

Scenario	No adaptation	With adaptation
GISS	-21.5	-8.7
GFDL	-37.8	-22.3
UKMO	-34.1	-19.4
OSU	-31.9	-20.9

Estimates of livestock production efficiency suggest that the negative effects of hotter weather in summer outweigh the positive effects of warmer winters (Adams *et al.*, 1999). The largest change occurred under a 5°C increase in temperature, when livestock yields fell by 10% in cow-calf and dairy operations in the Appalachia, southeast, Delta, and southern Plains regions of the United States. The smallest change was 1% under 1.5°C warming in the same regions. Livestock production also is affected by changes in temperature and extreme events. For example, an ice storm in eastern Canada and the northeast United States in the winter of 1998 had severe effects on livestock in the region (see Section 15.3.2.6).

15.2.3.1.5. Role of changing water resources

Although several studies have examined the potential implications of climate change for streamflows and water delivery reliability from reservoir systems in regions where irrigated agriculture is now important (see Section 15.2.1), there have been few direct analyses of the economic impacts on irrigated agriculture of changes in water availability. Some assessments of the impacts of climate change on agriculture in North America have relied on optimistic assumptions regarding the availability of irrigation water to offset precipitation deficiencies (Mendelsohn *et al.*, 1994). Other studies have attempted to estimate the impacts of projected climate change on the potential use of irrigation water. A study of potential climate change impacts on irrigation water use in the United States concluded, “The greatest impact of a warmer climate on the agricultural economy will be in the West where irrigators will be hard put to maintain even present levels of irrigation” (Peterson and Keller, 1990). That conclusion is based on first-order impacts of reduced water availability and does not consider possible earnings from sale or lease of water rights.

Studies of the impacts of drought events may provide useful insights into the impacts of substantial changes in seasonal streamflows that may result from climate warming—particularly in western North America, where mountain snowpacks now sustain streamflows into the summer months (see Section 15.2.1). However, the impacts of short-term droughts are an imperfect analog to long-term impacts of a drier climate because farmers are likely to adjust crop choices and farming practices as they acquire experience with any new climate regime.

Under some scenarios, demand for irrigation water declines (e.g., as a result of more rapid crop maturation and/or increased growing-season precipitation). Scenarios investigated for the U.S. National Assessment (Reilly *et al.*, 2000) suggest that demand for water resources by agriculture would decline nationwide on the order of 5–10% by 2030 and 30–40% by 2090. Land under irrigation showed similar magnitudes of decline. Crop yield studies generally favor rainfed over irrigated production and show declines in water demand on irrigated land. Such adaptations could help to relieve some of the stress on regional water resources by freeing water for other uses (Hurd *et al.*, 1999). However, the interplay between changes in irrigation demand and changes in water supplies has not been fully assessed.

15.2.3.1.6. Carbon sequestration

North American soils have lost large quantities of carbon since they first were converted to agricultural systems, leaving carbon levels in agricultural soils at about 75% of those in native soils (Bruce *et al.*, 1999c). Because carbon in agricultural soils is a manageable pool, it has been proposed that these soils be managed to sequester carbon from atmospheric CO_2.

15-1. Carbon Sequestration: Adaptation Issues

The Kyoto Protocol commits industrialized nations to take on binding targets for GHG emissions for the period 2008–2012. The Protocol mentions human-induced land-use changes and forestry activities (afforestation, reforestation, deforestation) as sinks of GHGs for which sequestration credits can be claimed; it also mentions that agricultural sinks may be considered in the future. As a result, a significant market is emerging in North America for ways to enhance carbon sequestration in these sectors. Although it is not within the purview of this section to deal with mitigation strategies, land management decisions impact a wide range of factors. There may be several consequent issues that result or are derived from implementation and adoption of these strategies. Negative consequences of reduced tillage implemented to enhance soil carbon sequestration may include (medium confidence):

- Increased use of pesticides for disease, insect, and weed management. This increased pesticide load may affect adjacent ecosystems and the quality of water within and outside agroecosystems.
- Capture of carbon in labile forms that are vulnerable to rapid oxidation if the system is changed. This may require that reduced-till systems be maintained for an extended period (which also would lengthen the beneficial aspects of reduced tillage).
- Reduced yields and cropping management options and increased risk for farmers (Would yield reductions and increased risk be compensated?).

Beneficial consequences of reduced tillage (especially no-till) may include (high confidence):

- Reduced input costs (e.g., fuel) for farmers, thereby increasing the economic profit margin
- Increased soil moisture and hence reductions in crop water stress in dry areas
- Reduction in soil erosion, which inhibits loss of carbon from erosional forces and preserves the natural land base
- The overall combination of these effects improves soil quality and the ability of soils to physically and chemically support plant growth, as well as conserving the continent’s natural resources.

The extent to which carbon will be sequestered in agricultural and forest systems will be related to practical economics and land-use policies. For example:

- Expansion of agricultural lands for carbon sequestration may increase competition with use of agricultural lands for traditional food and fiber production. The effect may be decreased food and fiber production, with subsequent increases in prices and decreases in exports for agricultural commodities.
- Land prices may change (e.g., increase) as a consequence of competition between crops for food and crops for mitigation strategies.
- Reduction of agricultural lands by transferring these lands to forestry to enhance carbon sequestration also may increase competition for food and fiber production, but the influx of land into forestry subsequently may decrease forestry prices.

Thus, a focus on carbon sequestration in ecosystems may result in the transfer of large quantities of land between agriculture and forestry and change the management of existing agricultural and forest ecosystems. These changes may provide opportunities for landowners, but they also may have implications for food and fiber production and ecosystem functions.

The rate at which carbon is lost has subsided for most agricultural soils, and carbon levels in some soils have been maintained or even begun to increase as conservation farming practices have been adopted in the past 15–20 years. On cultivated land, these practices include conservation tillage (i.e., reduction or elimination of tillage) and residue management, use of winter cover crops, elimination of summer fallow, and methods to alleviate plant-nutrient and water deficiencies and increase primary production (Lal *et al.*, 1998). Revegetation of marginal lands and modified grazing practices on pastures can be used to increase soil carbon levels. On degraded soils, preventing and controlling erosion and reducing salinization help to maintain or increase soil carbon. Greater adoption of these measures in the United States and Canada could result in agricultural soils more effectively capturing carbon from atmospheric CO_2.

However, these agricultural practices that are effective in building soil carbon also may result in greater emissions of other GHGs (e.g., N_2O). Therefore, research is needed to weigh the positive and negative effects of building up soil carbon with respect to the overall goals of reducing GHG emissions. Moreover, implementation of such mitigation strategies and their effects on adaptation need further evaluation from the perspective of practical economics and land management decisions (see Box 15-1).

Some scenario studies suggest that interactions between soil and atmosphere will occur under a positive feedback system as temperatures increase: Higher temperatures will cause greater decomposition of soil carbon, in turn causing greater emissions from soil of CO_2, which will enhance the greenhouse effect and cause even higher temperatures. However, there is evidence that negative feedback mechanisms also exist. Some experiments indicate that more primary production is allocated to roots as atmospheric CO_2 rises (Schapendonk *et al.*, 1997), and these roots decompose more slowly than those grown at ambient CO_2 levels (Van Ginkel *et al.*, 1997). Recent comprehensive analyses of field data of forest soils suggests that increased temperature alone will not stimulate decomposition of forest-derived carbon in mineral soil (Giardina and Ryan, 2000).

Analysis of yield trends for 11 major crops over the period 1939–1994 indicates that the rate at which yield increased ranged from 1% on average to more than 3% yr^{-1} (Reilly and Fuglie, 1998). Conservative extrapolation of yields implies that the average annual increase in yield for the 11 crops between 1994 and 2020 would range from 0.7 to 1.3% yr^{-1}. More optimistic estimates of growth rates indicate that yield increases could be as high as 3% yr^{-1}. These yield increases could lead to substantial increases in soil carbon if crop residues are retained.

15.2.3.2. Production Forestry

Evaluation of effects of climate change on production forestry are constrained by uncertainties discussed in Section 15.2.2.1 (i.e., state-of-the-art forest models and GCM predictions produce equal probabilities of "considerable forest dieback" and "enhanced forest growth"). Moreover, in many cases, site-specific conditions as well as history, human management, air pollution, and biotic effects (e.g., herbivory) are much stronger controllers of forest productivity than climate change or CO_2 enrichment (Eamus and Jarvis, 1989; Aber and Driscoll, 1997; Ollinger *et al.*, 1997; Goodale *et al.*, 1998), especially in mid-latitudes. Finally, lands managed for timber production are likely to be less susceptible to climate change than unmanaged forests because of the potential for adaptive management (Binkley and Van Kooten, 1994).

In a broader assessment for the United States, Sohngen and Mendelsohn (1999) used several GCMs, a variety of ecological models, and a dynamic economic model (with adaptation) to assess climate change impacts on the U.S. timber market. Under a broad range of climate and ecosystem model predictions, economic changes were positive, as a result of generally positive impacts of climate change on U.S. forest production and the ability of producers to adapt. Disturbances from insects and fire were assumed to increase, but the study also assumed that there would be salvage logging followed by planting of the right species for a new climatic regime. In a sensitivity analysis, in which the possibility of replanting with incorrect species was considered, economic impacts became negative as a result of reductions in available stocks and increased regeneration costs.

The foregoing uncertainty raises questions about evaluating impacts and developing adaptation strategies. For example, Woodbury *et al.* (1998) used a climate change scenario derived from four GCMs, results from experimental studies, and a probabilistic regional modeling approach and estimate that there is a high likelihood that loblolly pine (a major timber production species) growth is likely to decrease slightly over a 12-state region of the southern United States. However, they also estimate that there is a substantial chance of either a large decrease or a large increase in growth. How can this information be used by the timber industry? Should managers assume that there would be no problems with loblolly pine plantations? Should they increase the area of these plantations? Should they convert plantations to a more mixed plantation community? Should plantations be converted to "natural succession"? Crippling uncertainty of this type may lead this production industry (as well as others) to disregard climate change as a factor in planning.

Similar questions have been raised in northwest Canada (see Section 15.3.2.8). Within the Mackenzie Basin Impact Study (MBIS), debate about forest management concerned the scenario of reduced spruce yield and increased risk of losses from fire and insect damage (Hartley and Marshall, 1997; Rothman and Herbert, 1997). In the short term, a large number of pressing issues divert attention from long-term climate change (e.g., land-use planning, British Columbia's Forest Practices Code, treaty negotiations with aboriginal people, trade with the United States, protected area strategy). Adaptation to climate change requires information that is relevant to the context of the industry, particularly if there are implications for harvesting (Barrett, 1997; Fletcher, 1997).

15.2.3.3. Marine Fisheries

Climate-related variations in marine/coastal environments are now recognized as playing an important role in determining the productivity of several North American fisheries. For example, large changes in species abundance and ecosystem dynamics off the coast of California have been associated with changes in sea-surface temperatures (SSTs), nutrient supply, and circulation dynamics (Ebbesmeyer *et al.*, 1991; Roemmich and McGowan, 1995; Bakun, 1996). Similar relationships have been observed in the Bering Sea, the northeastern Pacific, and the Gulf of Alaska (Polovina *et al.*, 1995; Ware, 1995; Shuntov *et al.*, 1996; Beamish *et al.*, 1997; Downton and Miller, 1998; Francis *et al.*, 1998; Beamish *et al.*, 1999a, 2000) and in the North Atlantic (Atkinson *et al.*, 1997; Sinclair *et al.*, 1997; Hofmann and Powell, 1998). In the Gulf of Mexico, variations in freshwater discharge affect harvests of some commercially important species (Hofmann and Powell, 1998). Projected climate changes have the potential to affect coastal and marine ecosystems through changes in coastal habitats, upwelling, temperature, salinity, and current regimes. Such changes may affect the abundance and spatial distribution of species that are important to commercial and recreational fisheries (Boesch *et al.*, 2000).

Fishery management involves the difficult task of maintaining viable fish populations in the presence of difficult-to-predict shifts in resource availability, while regulating competition among harvesters for access to publicly managed, common-property fishery resources (McKay, 1995; Fujita *et al.*, 1998; Myers and Mertz, 1998; Roughgarden, 1998). Attainment of management objectives may be confounded by the fact that some fish stocks tend to fluctuate widely from year to year. These fluctuations may arise from natural causes that are unrelated to fishing pressure or be exacerbated by harvesting. The exact cause of a sudden shift in abundance often is poorly understood. Climate variations often play a role in natural fluctuations, although their role may be complex and indirect. For example, a climatic variation may affect phytoplankton and zooplankton abundance in some part of the ocean, with cascading effects through a chain of predator-prey relationships (Bakun, 1996). These processes may result in multiple and lagged impacts on the abundance of a harvested species. Because it is difficult to identify and predict such effects, climate variability constitutes a significant source of uncertainty for fishery managers.

The potential impacts of climate change on fish populations are equally difficult to predict. Some work has focused on the direct impacts of warmer temperatures on marine species (e.g., Wood and McDonald, 1997; Welch *et al.*, 1998a,b). However, Bakun (1996) notes that climate variables that are important on land (e.g., temperature and precipitation) may be relatively unimportant for organisms that live in the ocean. He identifies three basic processes (enrichment, concentration, and transport /retention) that influence the productivity and spatial distribution of marine fish populations but notes that very little is known regarding how these will change with global climate change. Efforts to assess the impacts of climate change on the U.S. fishery sector are severely hampered by our current lack of understanding of possible changes in fish populations. Markowski *et al*. (1999) performed a sensitivity analysis that examined the potential economic impacts of hypothetical changes in the abundance of selected fish populations, but the analysis is too hypothetical for use here.

Uncertainty regarding the magnitude and sources of variations in fish stocks also creates political stumbling blocks to effective fisheries management. Within single jurisdictions, competing harvesters and gear groups vie for shares of a “pie” whose dimensions are imperfectly known. In the case of international fisheries, cooperative harvesting agreements often have degenerated into mutually destructive fish wars when expectations have been upset by unforeseen changes in abundance or the spatial pattern of availability (McKelvey, 1997). For example, the Pacific Salmon Treaty foundered for several years because declining runs of southern coho and chinook salmon and increasing salmon abundance in Alaskan waters frustrated efforts to achieve a mutually acceptable balance of U.S. and Canadian interceptions of one another’s salmon stocks (Munro *et al.*, 1998; Miller, 2000a).

Accounts of the collapse of cod stocks off Newfoundland on Canada’s east coast have cited the inability of governments to effectively control fishing pressure and a natural shift to less favorable environmental conditions (Hutchings and Myers, 1994; Sinclair *et al.*, 1997; Hofmann and Powell, 1998). This case suggests that sustainable fisheries management will require timely and accurate scientific information on the environmental conditions that affect fish stocks and institutional flexibility to respond quickly to such information.

The western U.S.-Mexican border region is located between subtropical and mid-latitude ocean regions. Variations in temperature in this transition zone result in major fluctuations in fisheries productivity (Lluch *et al.*, 1991). In recent decades, this region of the Pacific has shown a trend toward warming and changes in regional productivity, independent of overexploitation. In a global warming scenario, the sardine population may decrease along the U.S.-Mexican Pacific Ocean border region, whereas the shrimp population may increase. Interdecadal natural climate variability, however, appears to be the most important sardine population modulator (Lluch-Cota *et al.*, 1997).

Available evidence suggests that there are likely to be impacts on fisheries arising, for example, from changes in current dynamics, temperature-dependent distribution, and food web dynamics. These impacts will be variable across species and locations and are difficult to forecast with any precision. Because the effects of exploitation and environmental change can be synergistic, it will be increasingly important to consider changing environmental conditions in future fisheries management (Boesch *et al.*, 2000; see Chapter 6 for further discussion).

15.2.4. Human Health

Global climate change would disturb the Earth's physical systems (e.g., weather patterns) and ecosystems (e.g., disease vector habitats); these disturbances, in turn, would pose direct and indirect risks to human health. Direct risks involve climatic factors that impinge directly on human biology. Indirect risks do not entail direct causal connections between climatic factors and human biology (McMichael, 1996; McMichael *et al*., 1996). Health care will significantly help people to adapt to climate change. Unfortunately, not everyone has adequate health care; for example, in 1996, nearly 18% of Americans did not have access to a doctor's office, clinic, health center, or other source of health advice or treatment (Miller *et al.*, 2000).

15.2.4.1. Potential Direct Health Impacts of Climate Change

15.2.4.1.1. Health impacts of thermal extremes

In a warmer world, heat waves are expected to become more frequent and severe, with cold waves becoming less frequent (Kattenberg *et al*., 1996). Increased frequency and severity of heat waves may lead to an increase in illness and death, particularly among the young (CDC, 1993), the elderly (Ramlow and Kuller, 1990; CDC, 1993; Semenza, 1999; Patz *et al.*, 2000), the poor (Schuman, 1972; Applegate *et al*., 1981), the frail and the ill, and those who live in the top floors of apartment buildings and lack access to air conditioning (Patz *et al.*, 2000), especially in large urban areas (CDC, 1989; Grant, 1991; Canadian Public Health Association, 1992; Kalkstein, 1993, 1995; Kalkstein and Smoyer, 1993a,b; Canadian Global Change Program, 1995; Environment Canada, 1995; Guidotti, 1996; Kalkstein *et al*., 1996a,b; Tavares, 1996; Last *et al.*, 1998). Other vulnerable people are those who take medications that affect the body's thermoregulatory ability (Marzuk *et al.*, 1998; Patz *et al.*, 2000).

Heat waves affect existing medical problems, not just those related to problems of the respiratory or cardiovascular systems (Canadian Global Change Program, 1995). Morbidity—such as heat exhaustion, heat cramps, heat syncope or fainting, and heat rash—also results from heat waves (Shriner and Street, 1998; Patz *et al.*, 2000).

In the United States, populations in northeastern and midwestern cities may experience the greatest number of heat-related illnesses and deaths in response to increased summer temperatures (Patz *et al.*, 2000). Recent episodes include the heat-related deaths of 118 persons in Philadelphia in 1993 (CDC, 1993), 91 persons in Milwaukee in 1995, and 726 persons in Chicago in 1995 (CDC, 1995; Phelps, 1996; Semenza *et al.*, 1996, 1999). This follows several episodes in the 1980s, particularly in 1980, 1983, and 1988 (CDC, 1995).

In Canada, urbanized areas in southeastern Ontario and southern Quebec could be "impacted very negatively" by warmer temperatures. An "average" summer in 2050 could result in 240–1,140 additional heat-related deaths yr^{-1} in Montreal, 230–1,220 in Toronto, and 80–500 in Ottawa, assuming no acclimatization (Kalkstein and Smoyer, 1993b). The significance of these estimates is demonstrated by the fact that a total of only 183 Canadians died as a result of excessive heat for the years 1965–1992 (Duncan *et al.*, 1998). Heat-related illness and death are largely preventable through behavioral adaptations, such as use of air conditioners and increased intake of fluids. In the United States, use of air conditioning is expected to become nearly universal by the year 2050 (U.S. Census Bureau, 1997a,b). Other adaptive measures include development of community-wide heat emergency plans, improved heat warning systems, and better heat-related illness management plans (Patz *et al.*, 2000).

Finally, it is important to note that in a warmer world, cold waves are expected to become less frequent. For example, in Saskatoon, Canada, the number of January days with temperature below –35°C could decrease from the current average of 3 days yr^{-1} to 1 day every 4 years (Hengeveld, 1995). Currently, more people die of cold exposure than heat waves. Therefore, an expected decrease in cold waves is likely to have a beneficial effect—a decrease in weather-related mortality.

15.2.4.1.2. Health impacts of extreme weather events

It has been postulated that there will be increases in the frequency and severity of extreme events, which may result in an increase in deaths, injuries, toxic contamination or ingestion, infectious diseases, and stress-related disorders, as well as other adverse health effects associated with social disruption, environmentally forced migration, and settlement in poorer urban areas (McMichael *et al.*, 1996). Adaptive measures to counter the health impacts of extreme events include improved building codes, disaster policies, warning systems, evacuation plans, and disaster relief (Noji, 1997).

15.2.4.1.2.1. Convective storms

There is some evidence of increases in the intensity or frequency of some extreme events at regional scales throughout the 20th century. Frequencies of heavy precipitation events have been increasing in the United States and southern Canada (Easterling *et al.*, 2000). Unfortunately, it is difficult to predict where these storms will occur and to identify vulnerable populations. In 1997, severe storms caused 600 deaths and 3,799 reported injuries in the United States.

Patients with specific allergies to grass pollen are at risk of thunderstorm-related asthma (Venables *et al.*, 1994; Celenza *et al.*, 1996; Hajat *et al*., 1997; Knox *et al*., 1997; Suphioglu, 1998). Thunderstorm-associated asthma epidemics in Melbourne, Australia (1987/1989), and London, England (1994), placed considerable demands on the health system. Several London health departments ran out of drugs, equipment, and doctors (Davidson *et al.*, 1996). It is unclear if this situation could arise in North America.

15.2.4.1.2.2. Floods

Floods also may become more frequent (see Section 15.2.1.3). All rivers are susceptible to flooding, and nearby populations are potentially vulnerable. In the United States, floods are the most frequent natural disaster, as well as the leading cause of death from natural disasters. The mean annual loss of life is estimated to be 146 deaths yr^{-1} (National Weather Service, 1992; Patz *et al*., 2000). In 1997, the Canadian Red River flood displaced more than 25,000 people (Francis and Hengeveld, 1998; Manitoba Water Commission, 1998).

During a flood, disaster relief workers may be at risk of injury. For example, 119 injuries were identified from medical claims of people engaged in sandbagging activities in the 1993 Midwest floods. Heat-related injury or illness (HRI), which occurs when the body can no longer maintain a healthy core temperature, was the most frequently reported injury diagnosis; a total of 23 HRI (19.3% of the 119 total injuries) were reported (Dellinger *et al*., 1996). HRI therefore is a potential problem in disaster relief situations, particularly if high ambient temperature and high humidity exist. Following a flood, flood victims may be at risk of post-traumatic stress disorder (PTSD) and depression, which are risk factors for suicide. Krug *et al*. (1998) showed that suicide rates increased from 12.1 to 13.8 per 100,000 population in the 4 years after floods. Inundations of sites that contain toxic wastes, sewage, animal wastes, or agrochemical products may result in immediate human exposure to wastes from floodwaters, contamination of edible fish, and long-term contamination of flooded living structures (see Sections 15.2.1.3 and 15.2.4.2.2.2).

15.2.4.1.2.3. Hurricanes

Climate models currently are unable to project accurately how hurricanes will change in the future. Today, an average of two hurricanes make landfall each year along the coastline of the continental United States (Hebert *et al*., 1993). There has been considerable interdecadal variability in the number of landfalling hurricanes in the United States (Pielke and Pielke, 1997). The Federal Emergency Management Agency (FEMA) declared fewer than 20 natural disasters annually in the 1950s and 1960s but more than 40 yr^{-1} in the 1990s (Miller *et al*., 2000). Hurricanes' strong winds and heavy rains cause injury, death, and psychological disorders (Logue *et al*., 1979; Patz *et al*., 2000). A total of 20–30% of adults who lived through Hurricane Andrew showed evidence of PTSD at 6 months and 2 years after the event (Norris *et al*., 1999).

15.2.4.1.2.4. Ice Storms

Milder winter temperatures will decrease heavy snowstorms but could cause an increase in freezing rain if average daily temperatures fluctuate about the freezing point. It is difficult to predict where ice storms will occur and identify vulnerable populations. The ice storm of January 1998 (see Section 15.3.2.6) left 45 people dead and nearly 5 million people without heat or electricity in Ontario, Quebec, and New York (CDC, 1998; Francis and Hengeveld, 1998; Kerry *et al*., 1999). The storm had a huge impact on medical services and human health. Doctors' offices were forced to close, and a large number of surgeries were cancelled (Blair, 1998; Hamilton, 1998). One urban emergency department reported 327 injuries resulting from falls in a group of 257 patients (Smith *et al*., 1998b).

15.2.4.1.2.5. Tornadoes

Although some evidence is available regarding increases in the intensity and frequency of some extreme weather events, it is not yet clear how tornadoes will be affected. The tornado of July 31, 1987, in Edmonton, Alberta, killed 27 people and injured 253 (Etkin *et al*., 1998). Trends in the United States appear to show a decreasing number of deaths since the 1950s, although data on the number of events causing deaths do not show a trend (Kunkel *et al*., 1999). Godleski (1997) reports that persons who endure tornadoes often experience a variety of stress responses, including depression, acute and post-traumatic stress disorders, substance abuse, anxiety, and somatization.

15.2.4.2. Potential Indirect Health Impacts of Climate Change

15.2.4.2.1. Vector-borne diseases

15.2.4.2.1.1. Encephalitis

In the midwestern United States, outbreaks of St. Louis encephalitis (SLE) appear to be associated with a sequence of warm, wet winters; cold springs; and hot, dry summers (Monath, 1980). In the western United States, a 3–5°C increase in mean temperature may cause a northern shift in the distribution of western equine encephalitis (WEE) and SLE outbreaks and a decrease in the range of WEE in southern California (Reeves *et al*., 1994). In Canada, the ranges of eastern equine encephalitis (EEE), snowshoe hare virus (SHV), and WEE probably would expand with global warming. All three already have been reported in Canada or adjacent U.S. states, albeit sporadically (McLean *et al*., 1985; Artsob, 1986; Tourangeau *et al*., 1986; Keane and Little, 1987; Heath *et al*., 1989; Carman *et al*., 1995; Duncan *et al*., 1998).

15.2.4.2.1.2. Malaria

In the United States, sporadic autochthonous malaria transmission was observed in New York and New Jersey during the 1990s (Layton *et al*., 1995; Zucker, 1996). Malaria is imported into Canada, however.

According to studies by Martens *et al*. (1995), Martin and Lefebvre (1995), and Duncan (1996), with global warming, malaria may extend northward into temperate countries. These studies note, however, that many of these countries had regular epidemics of malaria in the 19th century and the first half of the 20th century and that continued and increased application of control measures—such as water management, disease surveillance and prompt treatment of cases—probably would counteract any increase in vectorial capacity.

Malaria once prevailed throughout the United States and southern Canada (Bruce-Chwatt, 1988). As recently as 1890, the census recorded more than 7,000 malaria deaths per 100,000 people across the American South and more than 1,000 malaria deaths per 100,000 people in states such as Michigan and Illinois. It is important to note that diagnoses and reporting did not meet today's standards. By 1930, malaria had been controlled in the northern and western United States and generally caused fewer than 25 deaths per 100,000 people in the South. In 1970, the World Health Organization (WHO) Expert Advisory Panel on Malaria recommended that the United States be included in the WHO official register of areas where malaria had been eradicated.

In Canada, vivax malaria became widespread at the end of the 18th century, when refugees from the southern United States settled in large numbers as far north as "the Huron" in the aftermath of the American War of Independence. Malaria was further spread with the building of the Rideau Canal (1826–1832) (Duncan, 1996). By the middle of the 19th century, malaria extended as far north as 50°N. In 1873, the great malarious district of western Ontario was only a fraction of a large endemic area, extending between Ontario and the state of Michigan. In Canada, the disease disappeared at the end of the 19th century (Bruce-Chwatt, 1988; Haworth, 1988; Duncan, 1996).

The history of malaria in North America underscores the fact that increased temperatures may lead to conditions that are suitable for the reintroduction of malaria to North America. Socioeconomic factors such as public health measures will continue to play a large role in determining the existence or extent of such infections (Shriner and Street, 1998).

15.2.4.2.1.3. Dengue and Yellow Fever

Although the *Aedes aegypti* mosquito already is found in the southern United States, socioeconomic factors play a large role in determining the actual risk of climate-sensitive diseases (see Chapter 9). For example, socioeconomic differences between Texas and bordering Mexico determine disease incidence: A total of 43 cases of dengue were recorded in Texas during 1980–1996, compared to 50,333 in the three contiguous border states in Mexico (Reiter, 1999).

15.2.4.2.1.4. Lyme Disease and Rocky Mountain Spotted Fever

Lyme disease—the most common vector-borne disease in the United States—currently circulates among white-footed mice in woodland areas of the Mid-Atlantic, Northeast, upper Midwest, and West Coast of the United States (Gubler, 1998). In 1994, more than 10,000 cases of the disease were reported (Shriner and Street, 1998). Although possible tick vectors have been reported in various parts of Canada, self-reproducing populations of infected ticks are believed to occur only in Long Point, Ontario (Barker *et al.*, 1992; Duncan *et al.*, 1998). Lyme disease has been predicted to spread within Canada with increased temperatures (Grant, 1991; Canadian Global Change Program, 1995; Environment Canada, 1995; Guidotti, 1996; Hancock and Davies, 1997). However, in assessing climate-induced risks for Lyme disease, the ecology of two mammalian species along with projections for land use make predictions very difficult (see Chapter 9). Finally, Grant (1991) has suggested that, with warming, Rocky Mountain Spotted Fever might increase in some localities in Canada.

15.2.4.2.2. Rodent-borne diseases

15.2.4.2.2.1. Hantavirus

In 1993, Sin Nombre virus, which causes hantavirus pulmonary syndrome (HPS), emerged in the Four Corners region of the southwestern United States. Unusually prolonged rainfall associated with the 1991–1992 El Niño was implicated as a causal factor in the outbreak (Engelthaler *et al.*, 1999; Glass *et al.*, 2000). As of 1999, 231 cases had been confirmed in the United States, with a mortality rate of 42% (Patz *et al.*, 2000). A total of 16 cases of HPS have been identified in Canada. These cases occurred in British Columbia, Alberta, and Saskatchewan (Stephen *et al*., 1994; Werker *et al*., 1995; Duncan *et al.*, 1998).

HPS could undergo changes in occurrence related to increased contacts between rodents and people. Because the virus is present in rodents in the United States and Canada and changes in climate and ecology are known to affect rodent behavior, it is assumed that changes in the incidence of HPS would result with global warming (Duncan *et al.*, 1998), but they will be difficult to predict because of local rainfall variability.

Adaptive measures to reduce the risks of contracting vector- and rodent-borne diseases include providing information, vaccination, and drug prophylaxis for travellers, as well as use of repellants, surveillance, and monitoring (Patz *et al.*, 2000).

15.2.4.2.2.2. Diseases associated with water

More than 200 million people in the United States have direct access to treated public water supply systems. Nevertheless, 9 million cases of water-borne diseases are estimated to occur each year (Bennett *et al.*, 1987). Although most of the water-borne disease involves mild gastrointestinal illness, some disease causes severe outcomes, such as myocarditis (Patz *et al.*, 2000).

Giardia occurs in American and Canadian watersheds, resulting in widespread human exposure (Schantz, 1991; Chow, 1993; Moore *et al.*, 1993; Wallis *et al.*, 1996; Olson *et al.*, 1997;

Duncan *et al.*, 1998). A study of 1,760 water samples from 72 municipalities across Canada showed that giardia cysts were found in 73% of the raw sewage samples, 21% of the raw water samples, and 18.2% of the treated water samples (Wallis *et al.*, 1996). Cryptosporidium—considered to be one of the most common enteric pathogens worldwide (Meinhardt *et al.*, 1996)—is less common in Canada than giardia cysts, however. Cryptosporidium was found in only 6.1% of raw sewage samples, 4.5% of raw water samples, and 3.5% of treated water samples (Wallis *et al.*, 1996).

Increases in ambient temperatures, a prolonged summer season, increased heavy rainfall and/or runoff events, and many watersheds with mixes of intensive agriculture and urbanization led to recent large outbreaks of cryptosporidium in the United States (MacKenzie *et al.*, 1994; Goldstein *et al.*, 1996; Osewe *et al.*, 1996) and the UK (Bridgeman *et al.*, 1995) and may be indicative of the future. In 1993, more than 400,000 cases (including 54 deaths) resulted from a cryptosporidium outbreak in the Milwaukee, Wisconsin, water supply (MacKenzie *et al.*, 1994). A positive correlation between rainfall, cyrptosporidium oocyst and giardia cyst concentrations in river water, and human disease outbreaks has been noted (Weniger *et al.*, 1983).

The largest ever reported outbreak of toxoplasmosis was traced to the municipal water supply of the greater Victoria area of British Columbia (British Columbia Toxoplasmosis Team, 1995; Den Hollander and Noteboom, 1996; Mullens, 1996; Bowie *et al.*, 1997; Duncan *et al.*, 1998). There already is evidence that exposure to the causative parasite in Canada is widespread (Tizard *et al.*, 1977, 1978). Given the increasing number of feral cats in Canada and the persistence of sporulated oocysts in a variety of environments (Dubey and Beattie, 1988), areas in Canada that are hospitable to oocyst survival are likely to expand as a result of climate change.

Warm marine water may favor growth of toxic organisms such as red tides, which cause three varieties of shellfish poisoning: paralytic, diarrheic, and amnesic. Domoic acid—a toxin produced by the *Nitzchia pungens* diatom that causes amnesic shellfish poisoning—appeared on Prince Edward Island for the first time in 1987. A total of 107 patients were identified, of whom 19 were hospitalized. Of those requiring hospitalization, 12 people required intensive care because of coma, profuse respiratory secretions, or unstable blood pressure. A total of four people died as a result of eating contaminated mussels (Perl *et al.*, 1990). The outbreak coincided with an El Niño year, when warm eddies of the Gulf Stream neared the shore and heavy rains increased nutrient-rich runoff (Glavin *et al.*, 1990; Perl *et al.*, 1990; Teitelbaum *et al.*, 1990; Hatfield *et al.*, 1994; Shriner and Street, 1998). In the United States, marine-related illness increased during El Niño events over the past 25 years. During the strong El Niño event of 1997–1998, precipitation and runoff greatly increased counts of fecal bacteria and viruses in local coastal waters in Florida (Harvell *et al.*, 1999). Contamination of water bodies by animal and human wastes can stimulate harmful algae such as *Pfiesteria* that have been demonstrated to cause illness in humans and death in some species of fish (Burkholder *et al.*, 2000).

Potential adaptive measures to reduce water-borne disease include improved water safety criteria, monitoring, treatment of surface water, and sewage/sanitation systems (Patz *et al.*, 2000). Land-use management should include consideration of water supply and quality.

15.2.4.2.3. Respiratory disorders

In 1997, approximately 107 million people in the United States lived in counties that did not meet air quality standards for at least one regulated pollutant (Patz *et al.*, 2000). Climate change increases smog (NRC, 1991; Sillman and Samson, 1995; USEPA, 1998a; Patz *et al.*, 2000) and acidic deposition. Climate change is likely to have a positive (worsening) effect on suspended particulates (Maarouf and Smith, 1997). These changes would have an impact on human health. However, at this time there are too few studies on the effect climate change will have on all pollutants to project human health impacts. Studies (Bates and Sitzo, 1987, 1989; Tseng *et al.*, 1992; Burnett *et al.*, 1994; Delfino *et al.*, 1994, 1997; Schwartz, 1994; Thurston *et al.*, 1994) have demonstrated that hospital admissions for respiratory illnesses are increased during contemporary air pollution episodes, when levels of ozone, acid aerosols, or particulates are elevated (Campbell *et al.*, 1995).

Adaptive measures to changing pollution levels include federal legislation and warnings for the general population and susceptible individuals (Patz *et al.*, 2000).

15.2.4.2.3.1. Smog

More than half of all Canadians live in areas in which ground-level ozone may reach unacceptable levels during the summer months (Duncan *et al.*, 1998). Peak 1-hour concentrations during typical pollution episodes in the Windsor-Quebec City corridor often reach 150 ppb. Windsor exceeds standards for ozone air quality (82 ppb) 30 days yr^{-1} on average. In the Lower Fraser Valley, ozone concentrations typically are in the 90–110 ppb range during pollution episodes. In the Southern Atlantic region, peak hourly ozone concentrations are in the 90–150 ppb range (Duncan *et al.*, 1998).

Two expert panels from the Canadian Smog Advisory Program have listed a wide range of health effects of ground-level ozone at levels that plausibly may occur in Canada. These effects include pulmonary inflammation, pulmonary function decrements, airway hyper-reactivity, respiratory symptoms, possible increased medication use and physician/emergency room visits among individuals with heart or lung disease, reduced exercise capacity, increased hospital admissions, and possible increased mortality (Stieb *et al.*, 1995). The panels conceptualized potential health effects of air pollution as occurring in a logical “cascade” or "pyramid," ranging from severe, uncommon events (e.g., death) to mild, common effects (e.g., eye, nose, and throat irritation) and asymptomatic changes of unclear clinical significance (e.g., small pulmonary function decrements and pulmonary inflammation) (American Thoracic Society, 1985; Bates, 1992).

Healthy persons can demonstrate effects from ozone exposure when they have an increased respiratory rate (e.g., when they are involved in strenuous activities outdoors) (Brauer *et al.*, 1996). Ozone may pose a particular health threat, however, to those who already suffer from respiratory problems such as asthma, emphysema, or chronic bronchitis (Stieb *et al.*, 1996). These three conditions affect about 7.5% of the Canadian population (Ontario Lung Association, 1991). Ozone also may pose a health threat to young, elderly, and cardiovascular patients (Duncan *et al.*, 1998). An increase in smog also would pose a greater risk to African Americans, who have consistently higher rates of deaths and emergency room visits than caucasians (Mannino *et al.*, 1998).

15.2.4.2.3.2. Acidic deposition

Acidic aerosols—such as sulfur dioxide (SO_2), sulfates, and nitrogen dioxide (NO_2)—have a colloidal affinity to fine particulates, which provide the vector needed to penetrate deeply into the distal lung and airspaces. In general, NO_2 and SO_2 have acute negative impacts on the respiratory system (Campbell *et al.*, 1995).

Several studies (Bates and Sitzo, 1987, 1989; Tseng *et al*., 1992; Burnett *et al.*, 1994; Delfino *et al.*, 1994; Schwartz, 1994; Thurston *et al.*, 1994) have demonstrated that hospital admissions for respiratory illnesses increase during contemporary air pollution episodes when levels of ozone, acid aerosols, or particulates are elevated (Campbell *et al.*, 1995). A study by Raizenne *et al*. (1996) that examined the health effects of acid aerosols on children living in 24 communities in the United States and Canada found that long-term exposure had a deleterious effect on lung growth, development, and function. Dockery *et al.* (1996) found that children living in communities with the highest levels of strong particle acidity were significantly more likely to report at least one episode of bronchitis in the past year compared to children living in the least polluted communities.

15.2.4.2.3.3. Suspended particulates

Fine particulates are associated with respiratory symptoms, airway hyperreactivity, impaired lung function, reduced exercise capacity, pulmonary inflammation, pulmonary function decrements, increased number of emergency room visits for asthma, increased hospitalizations, increased absence from school or work, and increased mortality from cardiopulmonary disease and lung cancer. Children, the elderly, smokers, asthmatics, and others with respiratory disorders are especially vulnerable to particulate air pollution (Stieb *et al.*, 1995; Seaton, 1996; Choudry *et al.*, 1997; Duncan *et al.*, 1998; USEPA, 1998a).

15.2.4.2.4. Nutritional health

In the United States, food-borne diseases are estimated to cause 76 million cases of illness annually, with 325,000 hospitalizations and 5,000 deaths (Mead *et al.*, 1999). Future food importations are likely to be associated with increases in outbreaks of some viral, parasitic, and bacterial diseases, such as hepatitis A (Duncan *et al.*, 1998).

Many aboriginal communities undertake hunting, fishing, and other resource-based activities for subsistence. Climate change is likely to dramatically alter the abundance and distribution of wildlife, fish, and vegetation. As a result, food supplies and economic livelihoods of many First Nations peoples would be in jeopardy (Last *et al.*, 1998; Weller and Lange, 1999). Disappearance of traditional medicinal plants from areas populated by Native American and other indigenous peoples may likewise affect physical, mental, and spiritual well-being.

15.2.5. Human Settlements and Infrastructure

Large metropolitan centers and industrial areas are particularly vulnerable to global environmental change (Schmandt and Clarkson, 1992). Large cities are considered to be areas of high risk because warming could lead to problems such as heat stress, water scarcity, and intense rainfall. Other potential impacts vary with location. In Canada and the northern United States, for example, people in larger cities are expected to experience fewer periods of extreme winter cold (Born, 1996). Many coastal communities will be affected by rising sea levels and increased risk of storm surge, but the impacts will differ because of variations in local and regional factors (Nicholls and Mimura, 1998). Most people in North America live in land that now is considered coastal and subject to coastal weather extremes. This sector of the urban population is growing faster than the population as a whole—a trend that is expected to continue (Boesch *et al.*, 2000). Indeed, "25 percent of the buildings within 500 feet of U.S. coastlines are predicted to fall victim to erosion in the next six decades" (Associated Press, 2000). Cities that are vulnerable to regular flooding may experience changes in the timing, frequency, and severity of this hazard (Weijers and Vellinga, 1995). In addition, the risk of increased periods of drought will be a challenge, particularly for communities that already are struggling to cope with water management issues. Overall, climate change should reduce vulnerability to some hazards such as cold waves but increase it with respect to others such as sustained periods of extreme heat.

15.2.5.1. Demographic Pressures

The number of people in North America increased from 83 million in 1901 to 301 million in 1998 (Statistics Canada, 1999a; U.S. Census Bureau, 1999b). The number living in large urban communities of more than 750,000 people increased over this period from 6 million to more than 140 million. A higher share of the population in North America lives in large urban centers

(45% in 1995) than in any other region of the world (UNDP, 1999). These large population centers may be vulnerable to climate change.

Aging of the population is another important demographic trend in North America. Europe and Japan currently are adapting to an aging of the population that is just emerging in North America. These demographic trends also appear in native communities with individuals living to older ages: Elderly people who have lived away from reservations may return home for retirement. An older population typically is more vulnerable to climate extremes (McMichael, 1997).

15.2.5.2. Infrastructure Investments in Adaptation

Many systems have the potential to be impacted negatively by climate change, including drainage and water systems, roads and bridges, and mass transit (Miller, 1989). Communities can reduce their vulnerability and increase their resilience to adverse impacts from climate change through investments in adaptive infrastructure (Bruce *et al.*, 1999a).

Across North America, however, government spending on public infrastructure has been declining for some time, measured as a share of economic activity. Almost 3.5% of GDP was spent on a broad range of infrastructure projects in the early 1960s, compared to less than 2% in the 1990s (Statistics Canada, 1999b; USBEA, 1999).

Sustained lower spending has increased society's vulnerability to some hazards. The American Society of Civil Engineers, for example, has warned that many dams in the United States have exceeded their intended lifespan (Plate and Duckstein, 1998). More than 9,000 regulated dams have been identified as being at high risk of failing, and there may be significant loss of life and property from future failures.

Highways, bridges, culverts, residences, commercial structures, schools, hospitals, airports, coastal ports, drainage systems, communications cables, transmission lines, and other infrastructure have been built on the basis of historical climate experience (Bruce *et al.*, 1999a). Similarly, land-use practices and building codes have been developed to provide effective protection from the existing climate. Emerging knowledge about future climate pressures was not available when most investment decisions were made. This includes, for example, recent research into actions that can be taken to protect underground transit systems from the increased risk of intense rainfall and subsequent flooding (Liebig, 1997). Furthermore, building codes have been modified frequently over the years to reflect emerging information about safer construction techniques, but these changes have not been applied to existing structures.

Coastal communities have developed a variety of systems to manage exposure to erosion, flooding, and other hazards affected by rising sea levels, but some of these systems have not been maintained—increasing the difficulty of putting in place enhancements to address future risk. Similarly, consideration of investments in larger diameter storm sewers in communities that expect more periods of intense rainfall may be affected by the age of existing systems (Fowler and Hennessey, 1995; Trenberth, 1998). Urban expansion and population growth further complicate decisionmaking with respect to infrastructure investments.

15.2.5.3. Coastal Regions Particularly Vulnerable

The prospect of rising sea level is one of the most widely recognized potential impacts of climate change. Some parts of North America have been experiencing sea-level rise for thousands of years (Hendry, 1993; Lavoie and Asselin, 1998). Most climate models, however, project that the pace will accelerate in many regions. This acceleration would increase the difficulty of adaptation for human settlements and natural systems. The greatest vulnerability is expected in areas that recently have become much more developed, such as Florida and much of the U.S. Gulf and Atlantic coasts. Insured property value in Florida alone exceeds US$1 trillion (Nutter, 1999).

Titus and Richman (2001) have developed a data set of coastal land elevations by using digital-elevation models and printed topographic maps to determine areas that are vulnerable to sea-level rise along the U.S. Atlantic and Gulf coasts. Louisiana, Florida, Texas, and North Carolina account for more than 80% of the 58,000 km^2 that are vulnerable to sea-level rise.

Rising sea levels, in turn, can cause increased erosion to shores and habitat and may contaminate some freshwater bodies with salt (Mason, 1999). Climate extremes, such as hurricanes, can add to the adverse impact (Michener *et al.*, 1997). Sea-level rise and climate and weather extremes cause problems associated with beach erosion, siltation of waterways, and flood risk in coastal communities (Hanson and Lindh, 1996; Leatherman, 1996).

More than 65% of people in North America live in coastal communities (Changnon, 1992; see also Figure 15-2). This includes those who live near the Atlantic or Pacific oceans as well as those near the Great Lakes, where the impact of climate change is very different (see Sections 15.2.1 and 15.3.2.5). Accordingly, there is vulnerability across most of the region. Particular concern arises with regard to the combination of sea-level rise with other risks, such as storm surge. Salt intrusion and frequent flooding may adversely impact farming and manufacturing activity in low-lying areas (Gough and Grace, 1998).

Tourism frequently is the major industry in many coastal communities. The risk of beach erosion, siltation, and flooding may become an important challenge for some existing tourism sites, yet these same changes may open new opportunities for some other communities. Tourism has been and will continue to be affected by beach closures resulting from coliform from septic systems and sewage outflows during and following

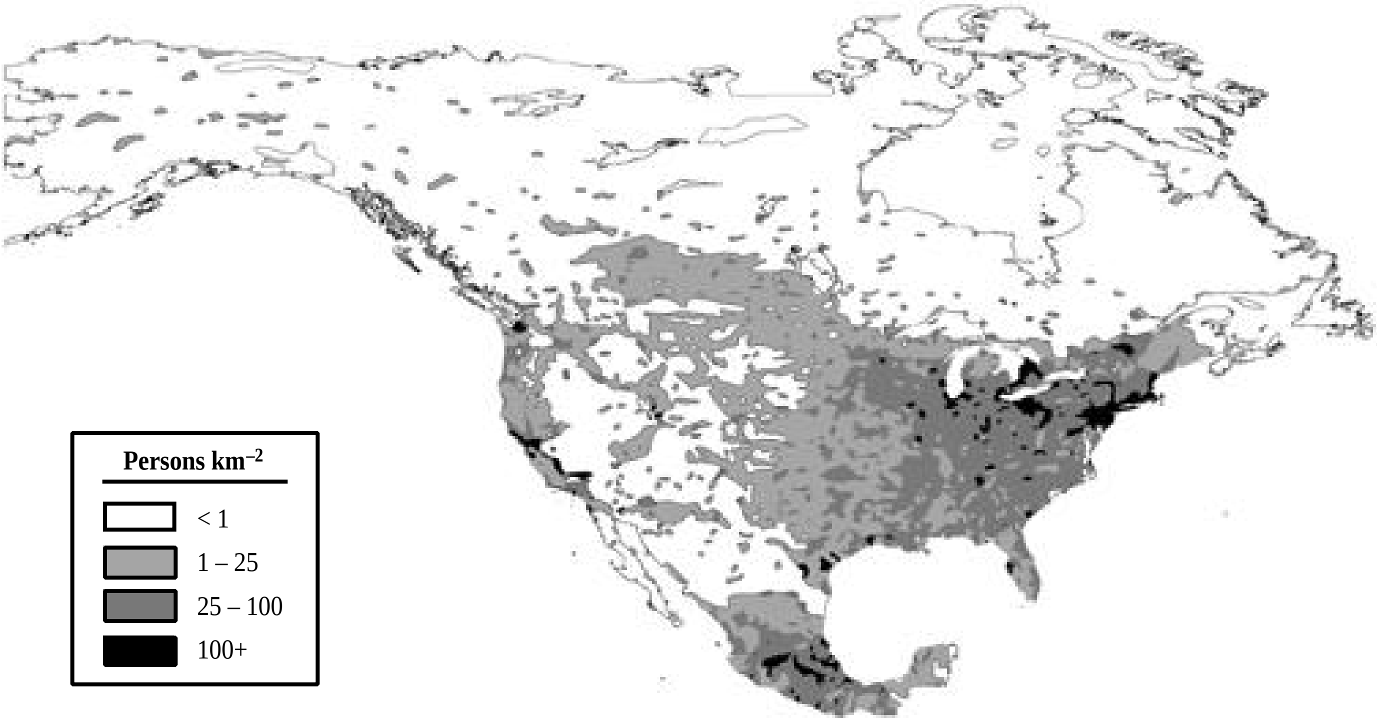

Figure 15-2: North American population density (ESRI, 1998).

storms and extreme events (see also Section 15.2.6). Sea-level rise also will be an important challenge for major ports in many parts of North America.

A study of the impact on the United States of the increase of sea levels through 2065 found losses of US\$370 million for dryland, US\$893 million for wetlands, and US\$57–524 million in transient cost (Yohe *et al.*, 1999). This estimate is much lower than those of earlier U.S. studies because of assumed adaptation responses, including decisions not to protect certain areas. No comparable information is available for Canada, although several vulnerable areas have been identified—particularly the Fraser River delta, Nova Scotia, and the Beaufort Sea region (Shaw *et al.*, 1998).

15.2.5.4. Vulnerability to System Failure

Investments in summer cooling, winter heating, and shelter from the elements are common for most people and businesses in North America. Similar investments are evident around the world, but the scope and scale often is greater in North America. For example, the percentage of homes with air conditioning units in the United States increased from 35% in 1970 (U.S. Census Bureau, 1975) to 76% in 1997 (U.S. Census Bureau, 1999a). Similarly, more vehicles, schools, hospitals, and businesses now have climate control mechanisms. Even traditional tasks have changed, such as air-conditioned cabs on farm vehicles.

The trend of warming across North America should reduce the cost of heating and the cost of investing in heating systems. At the same time, demand for summer cooling is expected to rise. In turn, changes in the weather affect demand for power: Peak demand for electricity is strongly correlated to swings in summer temperature (Colombo *et al.*, 1999).

Investments to manage normal fluctuations in the weather presumably have been effective in increasing the comfort of people in North America. These investments, however, also have increased vulnerability to systems failure. This could become most evident for most people in North America during a summer heat wave or a winter storm, when a failure in major support systems could place many people at risk. For example, in January 1998, a severe ice storm caused a power failure in Quebec and eastern Ontario (see Section 15.3.2.6).

A similar investment is in human alteration of hydrological drainage systems, including building of dikes, which may be an important factor in determining the severity of flooding (Changnon and Demissie, 1996). These interventions appear to be successful in managing most variations in the weather, but they can increase vulnerability to extreme events as new investments are made in regions that were thought to be sheltered from severe weather.

15.2.5.5. Development and Vulnerability to Extreme Events

The cost of natural disasters in North America has increased dramatically since the mid-1980s, in spite of the goal of the International Decade for Natural Disaster Reduction (the 1990s) to reduce the costs of natural disasters by 50% by the year 2000. Although an increase in the number of storms may play a role in these disasters, there is no question that the increasing costs are largely the result of increased vulnerability (Pielke and Downton, 2000).

Natural disasters occur when social vulnerability is triggered by a natural event (see Figure 15-3). Society responds to a disaster through three overlapping activities: response and recovery, mitigation, and preparedness. These activities alter future vulnerability (and therefore the construct of future disasters)—reducing risk if they are done wisely, or not if they are done otherwise. Often, however, mitigation that is designed to protect against natural hazards increases long-term vulnerability (Burton *et al.*, 1993). An example is the levee system planned for the Grand Forks region, as part of the post-1997 Red River flood mitigation scheme. NHC/DRI (1999) notes, "If the levee system is constructed as planned…[it will] have the potential to greatly increase damage and losses if the levee is breached or overtopped in a future flood."

Superimposed on the changing development landscape is the possibility that climate warming will reduce the risk of some extreme events and increase the risk of others (Karl *et al*., 1996; White and Etkin, 1997). Changes in the frequency, severity, and duration of extreme events may be among the most important risks associated with climate change. In some parts of North America, this includes fewer periods of extreme cold, fewer snowstorms (although there may be an increase in the number of intense storms), increased spring flooding, more frequent summer droughts, and more wildfires. Studies also suggest that there will be a more thermodynamically unstable atmosphere in the future, which probably will result in more frequent heavy rainfalls and possibly increased hail risk and more tornadoes and downbursts (Etkin, 1996).

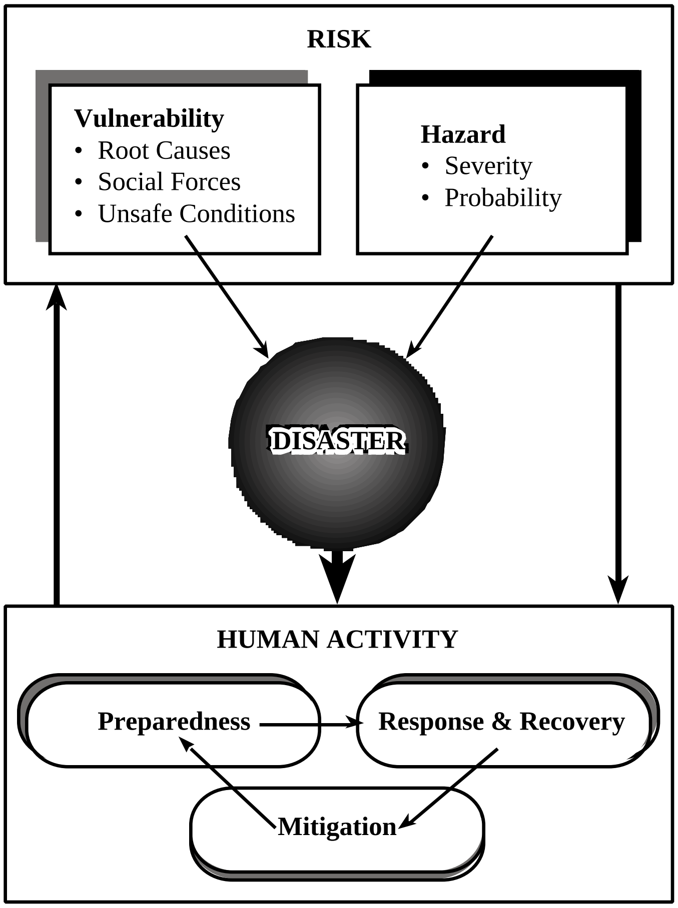

Figure 15-3: Cycle of human response to natural hazards, including response and recovery, mitigation, and preparedness. This response can alter vulnerability and thereby influence future disasters (Etkin, 1999).

Studies suggest that El Niño and La Niña events may become more frequent in the future, although there is still much uncertainty regarding predictions of tropical phenomena (Henderson-Sellers *et al.*, 1998; Timmermann and Oberhuber, 1999). Any changes would affect the number of extreme events, including the occurrence of Atlantic hurricanes because during El Niños (La Niña), Atlantic hurricanes are less (more) frequent. Landsea *et al.* (1999) point out that recent intensification of urban development along the U.S. Atlantic coast parallels a reduction of hurricane activity from 1966 to the early 1990s; they ask whether the United States is prepared for a recurrence of higher frequencies.

North American measures of property damage from severe storms are consistently higher and the loss of life lower, compared to less-developed countries. Investments in warning systems and disaster preparedness save lives. When these systems are overwhelmed by extreme events, however, the damage can be catastrophic. It is interesting that housing losses from extreme events generally are on the same scale in North America as those in developing countries, particularly when disaster strikes large urban centers (Comerio, 1997).

Older buildings often experience the greatest damage during extreme events. New buildings, however, also are at risk if insufficient effort is made to ensure compliance with building codes. Studies show that compliance with building codes may have eliminated up to 25% of insured losses resulting from major hurricanes (IBHS, 1999).

Damage from flooding in North America has increased in the past few decades (Mileti, 1999). Land-use planning remains a powerful tool to help reduce the loss of life and property. One study that indirectly illustrates this concept is Brown *et al.* (1997a). They found that nonagricultural flood damage from a set of storms moving through Michigan exceeded that of southwestern Ontario by a factor of about 900, even though the flood yields in Ontario were greater than those in Michigan. Their analysis ascribes the cause as greater development in flood-prone areas. In Michigan, the storms generally exceeded land-use design thresholds, whereas in Ontario they did not.

Munich Re (1997) found that "the extent of loss has not infrequently been increased through a false assessment of the risk circumstances or in the pursuit of profit." If the amount of development arising from the perception of reduced short-term risk tends to be disproportionate to the real increased risk from rare events, long-term vulnerability is increased. Mileti (1999) argues that "…our national [U.S.] path also is leading us toward natural and related technological catastrophes in the next millennium that are larger than any we have ever experienced …that is the future we have designed for ourselves.… [We] have done more to postpone losses into the future than to eliminate them." Social and economic trends suggest overall increases in vulnerability; if natural triggers of disasters are exacerbated as a result of climate change, it seems likely that more frequent and severe natural disasters are going to occur in the future (see Section 15.2.7).

15.2.6. Tourism and Recreation

Tourism is a major sector of the global economy, with global receipts from international tourism of US$439 billion in 1998. With a projected annual growth rate of 6.7%, annual international tourism expenditures are expected to surpass US$2 trillion by 2020 (WTO, 1998). The United States and Canada were among the top 10 tourism destinations in terms of international tourist arrivals, with related 1998 receipts of US$71 billion and US$9 billion, respectively (WTO, 1999). Domestic tourism is many times more important in terms of participation and economic activity. The magnitude of the implications of climate change for the tourism and recreation sector will depend on the distribution and importance of tourism and recreation phenomena and the characteristics of climate change and variability. In the United States, the Pacific and south Atlantic regions are major providers of tourism and recreation opportunities. However, if population distribution is taken into consideration, less populated areas often have high economic dependence on tourism and recreation.

One critically important dimension of the tourism and recreation sector that will be sensitive to climate change is the length of the operating season. Any changes in season length would have considerable implications for the short- and long-term viability of tourism and recreation enterprises. In Canada, where 43% of domestic and 62% of international tourism expenditures take place in July through September, an extended warm-weather recreation season is likely to be economically beneficial (Wilton and Wirjanto, 1998). The limited regional studies of golfing, camping, and boating that are available reinforce this conclusion (Wall, 1998a,b). This positive outlook must be tempered with the possibility that economic benefits may occur at the expense of increased environmental deterioration, as destinations host more visitors for longer periods of time. These concerns will be particularly relevant for national parks and other natural areas, which may need to establish "no-go" zones or visitation limits.

Conversely, winter recreations—such as downhill skiing, cross-country skiing, snowmobiling, ice fishing, and other activities that are dependent on snow or ice—as well as the businesses and destination areas associated with them are likely to be impacted negatively. Case studies from the Great Lakes (McBoyle and Wall, 1992) and New England (Bloomfield and Hamburg, 1997) regions indicate that the vulnerability of ski resorts will differ considerably, depending on location (latitude and altitude) and adaptations (snowmaking) to offset or compensate for the effects of less reliable snow conditions. Another potential adaptive strategy is diversification of activities to ensure that investments in property and infrastructure generate income and employment for much of the year. Without analysis of the impacts of altered snow conditions for major ski areas in the mountain ranges of western Canada and the United States and the large snowmobile industry in both nations, the economic impact to the winter recreation sector in North America remains uncertain.

Perhaps as important as changes to season length will be the impact of climate change on the availability and quality of the resource base on which recreational activities depend. Below-average Great Lakes water levels in 1999 again revealed the sensitivity of marinas and the substantial recreational boating industry to climate variability. Similarly, the impact of the 1988 drought on Prairie wetlands and waterfowl breeding success is illustrative of the potential impact of climate change for this sport-hunting resource. Global warming is anticipated to modify many other ecosystems on which outdoor recreations depend. Parks and other natural areas are important tourism and recreation resources whose attractions are based to a considerable extent on the species they conserve and the ecological processes they sustain. A climate change assessment of Canada's National Park system (Scott and Suffling, 2000) indicates that 75–80% of the parks would experience a shift in dominant vegetation under $2xCO_2$ scenarios. Analysis of vegetation response in the Yellowstone National Park region in the United States revealed regional extinctions and the emergence of communities with no current analog (Bartlein *et al.*, 1997). Moreover, a global analysis of habitat change resulting from climate change found that more than 50% of the territory of seven Canadian provinces and greater than 33% of the territory in 11 U.S. states are at risk (Malcolm and Markham, 2000). Although this will pose an unprecedented challenge to the conservation mandate of protected areas, the impact of ecological changes on tourism remains uncertain.

Changes in the magnitude and frequency of extreme events such as hurricanes, avalanches, fires, and floods have considerable implications for tourism and recreation. One likely consequence of global climate change is sea-level rise. This may have considerable consequences for the provision of recreational opportunities in coastal communities, particularly if it is associated with increased storm frequency.

Coastal zones are among the most highly valued recreational areas and are primary tourist destinations. Houston (1996) estimates that 85% of all tourist revenues in the United States are earned by coastal states, and there are as many as 180 million recreational visitors to U.S. coasts every year (Boesch *et al.*, 2000). Sea-level rise in beach areas backed by seawalls or other development that precludes landward migration would lead to loss of beach area through inundation or erosion and pose an increased threat to the recreation infrastructure concentrated along the coast (sea-front resorts, marinas, piers, etc.). Beach nourishment is widely used to protect highly valued recreational beaches. One study estimates that this adaptation strategy would cost US$14–21 billion to preserve major U.S. recreational beaches from a 50-cm sea-level rise (Wall, 1998c). Furthermore, impacts to ecologically important wetlands and coral reefs also could have major implications for sport fishing and diving-related tourism activities in coastal regions. The risk to coastal recreation is most prominent in warm-weather destinations in the southern United States and small island nations in the Caribbean (see Chapter 17 and Section 15.3.2.10), where tourism is a leading sector of the economy.

Intersectoral resource competition also may become more pronounced, particularly with respect to water resources. Climate change scenarios for the Trent-Severn Waterway (Walker, 1996) indicate that regulation of flows for adequate downstream municipal demand would diminish the recreational boating industry, with attendant impacts for riparian recreational home property values. Increased municipal and agricultural water demand in arid regions may outweigh development of new golf courses and, in severe cases, diminish the capacity to irrigate existing facilities economically. Like declining resource availability and quality, increased resource competition may constrain the opportunities afforded by a longer recreational season.

Two main groups can be considered with respect to the potential to adapt to climate change: participants themselves and businesses and communities that cater to them. The former may be able to adapt to climate change much more readily than the latter, which are more likely to have large amounts of capital invested in fixed locations. The effect of and potential for substitution as an adaptive strategy, including locations (beach, ski resort), preferred species (coldwater vs. warmwater fish), and recreational activities broadly (skiing to mountain hiking, snowmobile to all-terrain vehicle use, golf to sailing) require more detailed investigation.

Tourism and recreation are not regarded as major net generators of greenhouse gases (except, perhaps, in the travel phase), but GHG reduction policies (e.g., carbon taxes) may increase the cost of travel, with substantial implications for destination areas (particularly isolated destinations with little domestic tourism demand).

Improvement in climate change projections, although helpful, will be insufficient to improve understanding of the implications of climate change for tourism and recreation. Even if climate change could be reliably forecast now, it is doubtful if the industry has sufficient understanding of its sensitivity to climatic variability to plan rationally for future conditions. Furthermore, the salience of climate change versus other long-term influencing variables in this sector (globalization and economic fluctuations, fuel prices, aging populations in industrialized countries, increasing travel safety and health concerns, increased environmental and cultural awareness, advances in information and transportation technology, environmental limitations—water supply and pollution) remains a critical source of uncertainty.

Global climate change will present challenges and opportunities for recreational industries and destination areas. The net economic impact of altered competitive relationships within the tourism and recreation sector is highly uncertain. Studies by Mendelsohn and Markowski (1999) and Loomis and Crespi (1999) attempt to put an economic value on climate change impacts in the United States. Although these were pioneering efforts, the assumptions and methods employed limit the confidence that can be placed in the findings. Until systematic national-level analyses of economically important recreation industries and integrated sectoral assessments for major tourism regions have been completed, there will be insufficient confidence in the magnitude of potential economic impacts to report a range (based on disparate climate, social, technical, and economic assumptions) of possible implications for this sector.

15.2.7 Public and Private Insurance Systems

The North American economy is widely affected by weather conditions. The Chicago Mercantile Exchange stated recently that weather affects US$2 trillion of the US$9 trillion gross national product (GNP). Insurance is a critical part of the vulnerability/adaptation equation because many of the economic risks and impacts of weather-related events are diversified and ultimately paid through insurance.

The discussion in the following subsections embraces public and private insurance systems, as well as disaster relief. Within the private insurance sector are many actors, including property/casualty (P/C) insurers, life/health insurers, reinsurers, self-insurers, and various trade allies (risk managers, brokers, agents, etc.). Within the public sector are direct insurance programs, as well as disaster preparedness and recovery activities. Other segments of the financial services sector appear to be less vulnerable and are treated in Chapter 8.

15.2.7.1 Private-Sector Insurance Systems

Private insurance is among the largest economic sectors in North America, with about 40% (US$780 billion) of global premium revenues in 1998 (Swiss Re, 1999). North American premiums represent 9% of GDP, or about US$2,600 per capita. Despite its size, the industry is hardly a monolith; there are numerous types of insurance companies and market segments (Mills *et al.*, 2001).

Weather-related loss data presented here are based on diverse sources, and the particular costs included can vary somewhat among countries and over time. In some cases, definitions set minimum thresholds for inclusion; for example, because of the minimum cost threshold of US$25 million in the U.S. (formerly US$5 million), no winter storms were included in the statistics from 1949–1974, and few were included thereafter (Kunkel *et al.*, 1999). Although large in aggregate, highly diffuse losses from structural damages as a result of land subsidence also would be captured rarely in these statistics. Data-gathering conventions can result in omission of certain types of costs (e.g., weather-related vehicle losses). Thus, the totals presented here are inherently underestimates of actual losses.

Although North America experienced 59% of global weather-related insurance losses and 36% of total economic losses during the 1985–1999 period, it experienced only 20% of the events and 1% of associated mortalities (see Figure 15-4). Total economic losses (insured and uninsured) from weather-related events represented US$253 billion (current dollars) during this period. Of that total, 38% (US$96 billion) were privately insured, with considerable year-to-year fluctuations in the ratio.

During this period, weather-related natural disasters represented 82% of total natural disaster losses in the United States and virtually the entire total in Canada (where significant earthquake losses have not occurred). Although considerable attention is given to catastrophic losses, half of all insured weather-related losses are from relatively small events (see Chapter 8).

Inflation-adjusted catastrophe losses have been growing in North America over the past 3 decades (see Figure 15-5). Corresponding exposures, measured as the inverse of the ratio of premium income to losses, have been growing (i.e., if the ratio goes down, exposure goes up); the ratio has varied by a factor of six in the United States between 1974 and 1999, and by a factor of four in Canada between 1987 and 1999 (see Figure 15-6).

Although many of the upward trends in weather-related losses are consistent with what would be expected under climate change (see Chapter 8), efforts to disentangle socioeconomic and demographic effects from climatic factors have had mixed results in the United States (Changnon *et al.*, 1997, 2000; Karl and Knight, 1998; Pielke and Landsea, 1998; Changnon, 1999). In Canada, there is a stronger sense that both factors are at work (White and Etkin, 1997; Hengeveld, 1999).

Irrespective of climate changes, it is clear that human exposure is increasing with affluence and as populations continue to move into harm's way. The estimated value of insured coastal property exposure for the first tier of counties along the Atlantic and Gulf Coasts as of 1993 was US$3.15 trillion (IIPLR and IRC, 1995).

Most types of weather-related events—rain, hail, ice storms, tidal surges, mudslides, avalanche, windstorm, drought, land subsidence, lightning, and wildfire—are of concern to insurers (Ross, 2000). Corresponding losses can range from property damage to business interruptions and temporary housing costs as a result of loss of electric power. Coastal erosion is an important consequence of sea-level rise and already is responsible for a considerable and growing rate of losses (Heinz Center, 2000). Insurance in North America originally focused on fire peril; only since the late 1930s have insurers provided broad-based coverage for weather-related events (Mills *et al.*, 2001).

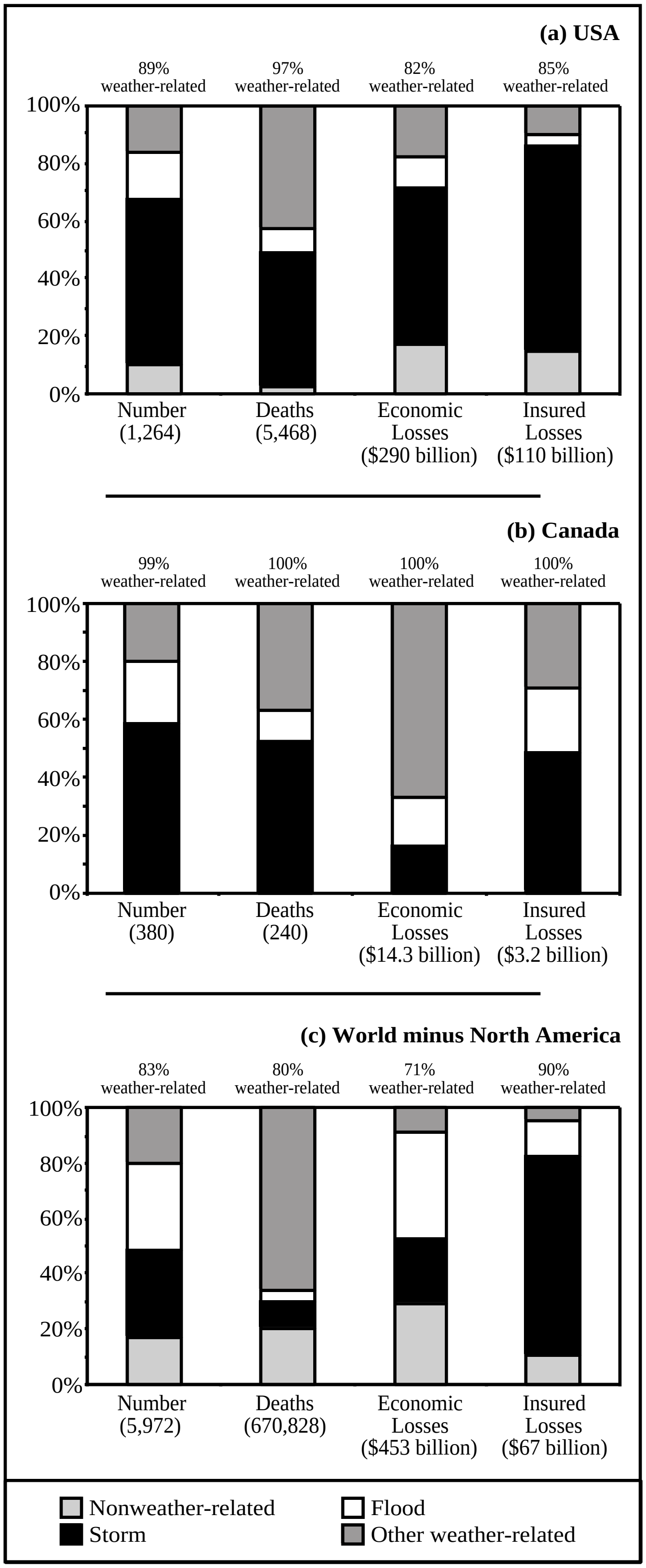

Figure 15-4: Distribution of natural-disaster losses in (a) Canada, (b) the United States, and (c) globally: 1985–1999 (Munich Re, 2000). "Storm" includes hurricanes, tornadoes, and high winds. "Other" includes weather-related events such as wildfire, landslides, avalanches, extreme temperature events, droughts, lightning, frost, and ice/snow damages.

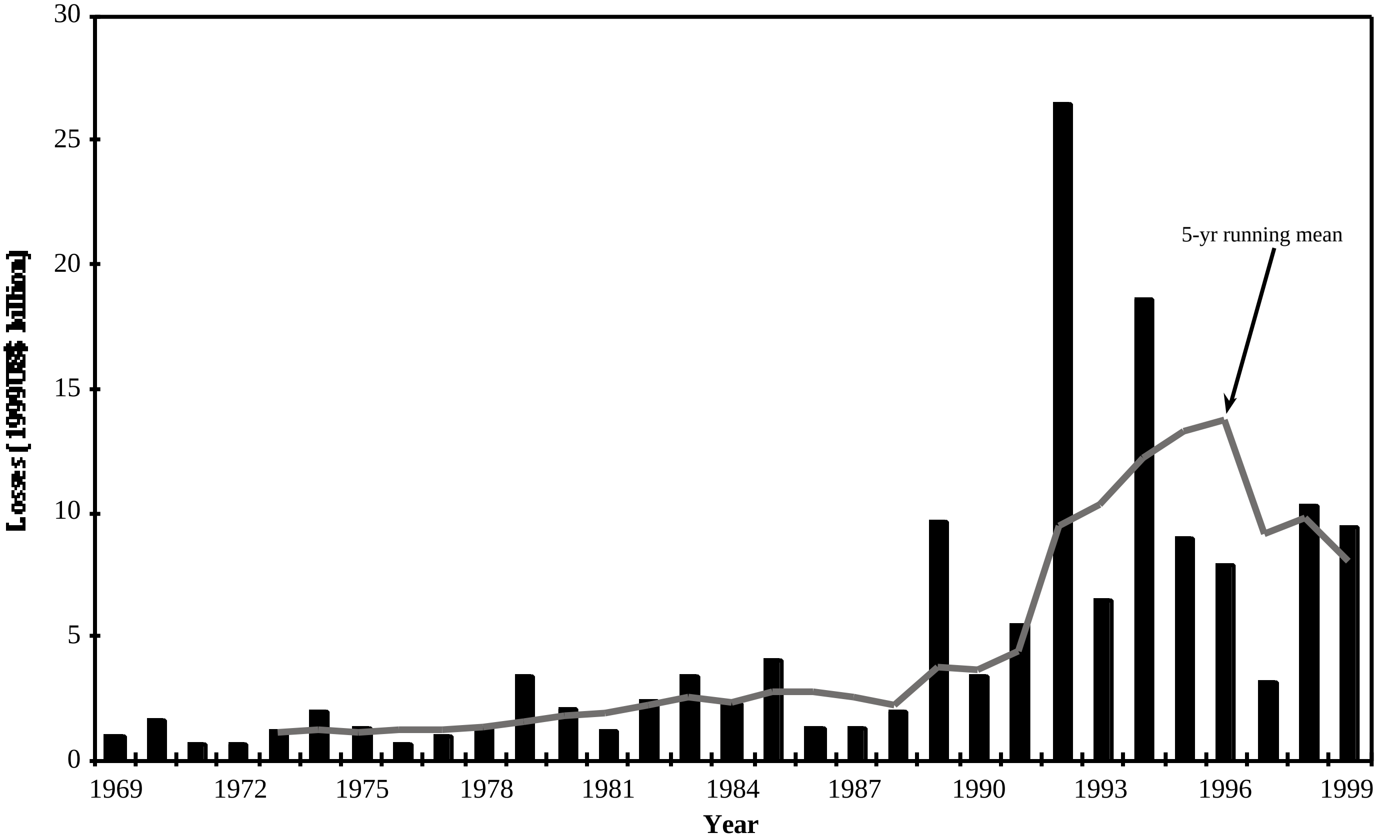

Figure 15-5: Insured natural disaster losses have increased 10-fold in North America between 1969 and 1999 (based on 5-year running mean). Data include nonweather-related losses (~15% of total). Sources: Emergency Preparedness Canada, 2000; Kunreuther and Roth, 1998 (United States).

The types of weather-related losses vary considerably between the United States and Canada. As shown in Figure 15-4, storm-related losses, including hurricanes, represent a larger share of losses in the United States, whereas flood and other weather-related events represent a far higher share in Canada. Large hurricane losses are substantial in the United States but have been virtually absent in Canada since Hurricane Hazel in 1954. Flood and storm events (other than hurricanes) have accounted for 95% of Canada's recent weather-related losses.

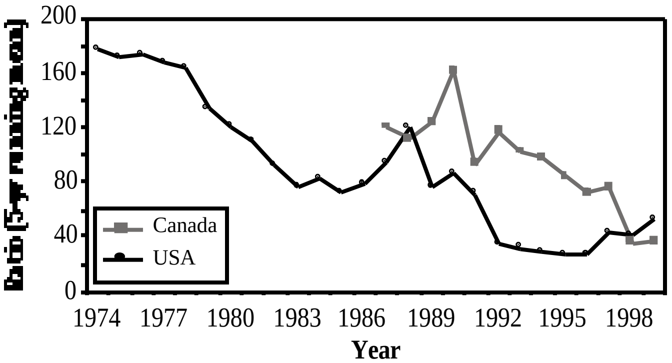

Figure 15-6: Ratio of property/casualty insurance premiums to catastrophe losses. This measure of exposure ranges from 180:1 in 1974 to 52:1 in 1999, with a minimum value of 27:1 in 1992 (the year of Hurricane Andrew). For Canada, the high value is 161:1 in 1990, and the low value is 37:1 in 1999. U.S. premiums are from AM Best and insured natural catastrophe loss figures are from Property Claims Service (Kunreuther and Roth, 1998). Canadian premiums are from Insurance Bureau of Canada (2000) and losses are from Emergency Preparedness Canada (2000). Note that premiums include revenues from nonweather-related business segments.

North American insurers have demonstrated sensitivity to the extremes and uncertainties of weather-related events. The trend in recent decades is toward increasing adverse impacts such as rising losses, upward pressure on prices, availability problems, company insolvencies, depressed stock prices, and increased reliance on government-provided insurance and disaster preparedness/recovery resources (see Chapter 8). P/C industries in the United States (see Chapter 8) and Canada (Emergency Preparedness Canada, 2000) have observed reduced and even negative operating results in years with large natural disaster losses.

A U.S.-based insurance trade association estimates that in 1997, 17% of U.S. insurance P/C premiums were associated with "significant" exposure to weather-related loss, 2% with "moderate" exposure, 66% with "minor" exposure, 10% with "minor to no" exposure, and 4% with "no" exposure (American Insurance Association, 1999). In these estimates, "exposure" is measured in terms of insurer premiums as opposed to the value of exposed property. Most flood and crop risks are not included because government insurance programs assume them. The “minor exposure” segment is mostly vehicle insurance. However, in the United States, 16% of automobile accidents are attributed to adverse weather conditions (NHTSA, 1998), as are one-third of the accidents in Canada (White and Etkin, 1997). Vehicles also sustain privately insured losses from floods and hailstorms.

In practice, insurer surplus is not poolable. Even at an industry-wide level, insurance pricing can be inadequate to cover future losses. This was evident in the case of the Northridge earthquake in California, where the US$3.4 billion in earthquake premiums collected during 25 years prior to the event fell far short of the US$15.3 billion loss (Gastel, 1999). Individual firms can come under stress long before the industry does as a whole. U.S. P/C insurers experienced approximately 650 insolvencies (bankruptcies) between 1969 and 1998, 8% of which were caused primarily by natural disasters (Matthews *et al.*, 1999). These disaster-related insolvencies include small as well as very large firms (see Chapter 8). Meanwhile, no recorded Canadian insurance insolvencies have been attributed to extreme events.

Insurers’ ability to withstand weather-related losses is based on a combination of event magnitude and resources (often referred to as assets or surplus) with which they can pay claims.

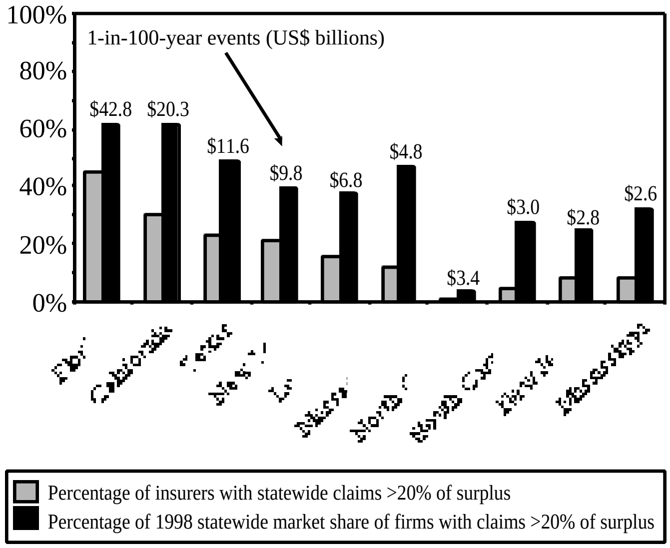

Figure 15-7: Vulnerability of U.S. insurers to 100-year events, represented as combined effect of loss magnitude and insurance company capacity (GAO, 2000). This analysis assumes that all insurers place and price policies identically. It excludes reinsurance, as well as local government-supported insurance or reinsurance programs in California and Florida. It also excludes effects of catastrophes striking more than one state (e.g., estimated 1-in-100-year loss for the entire United States is $155 billion). Capacity implied may include some surplus amounts that are not available for paying natural catastrophe claims. Losses that result in claims of more than 20% of surplus trigger initial stage of formal solvency review by National Association of Insurance Commissioners. Puerto Rico (not shown) has a 1-in-100-year loss of US$27.1 billion.

Probable maximum losses (PMLs) and vulnerability vary by locality and have been on the rise (Davidson, 1996; Cummins, 1999; GAO, 2000). As illustrated for the United States, natural disasters that are limited to the boundaries of a given state have widely varying potential impacts on insurers, depending on the capacity for paying losses (see Figure 15-7). Insurers have not performed quantitative analyses of the potential effects of climate change on PMLs.

Surplus—a measure of adaptive capacity—tends to be unstable over time, sometimes changing abruptly in response to perturbations in stock and bond market valuations or interest rates (Mooney, 1999; GAO, 2000; Swiss Re, 2000). Although U.S. insurer capacity increased considerably through the 1990s, as illustrated in Figure 15-8, large events still can result in a substantial volume of unpaid claims. Adaptive capacity can be depleted by multiple sequential events (AIRAC, 1986), as well as by past nonweather-related losses [e.g., from environmental liability (Superfund)]. There also are potential losses stemming from issues such as tobacco liability or the combination of increasing reliance on information technology and emerging questions regarding the reliability of the electricity grid. The finding that U.S. electric cooling demand would increase under global warming (Morrison and Mendelsohn, 1999) would be a compounding factor in the latter example, and adaptation (e.g., increased use of air conditioning) would result in increased GHG emissions. The trend toward increased competition is an additional stress on insurers, although consolidation also can—under the proper circumstances—increase resilience of firms.

An insurer’s vulnerability often extends beyond the borders of the country in which it resides. For example, U.S. insurers collected US$35 billion in premiums for overseas insurance sales in 1997, and such insurance has been growing faster than overall premiums in recent years (III, 1999). Canadian insurers also write policies outside the country, including vulnerable parts of the United States (White and Etkin, 1997). Reinsurers (many which are based in North America) have a high degree of vulnerability given the geographical diversity of their risk portfolios.

15.2.7.2 Government-Based Insurance and Disaster-Relief Systems

Government entities are vulnerable to climate change as providers of insurance and/or disaster relief; providers of domestic and international disaster preparedness/services; and managers of property and weather-sensitive activities.

Private insurers find certain weather-related risks to be technically uninsurable as a result of their spatial concentration, actuarial uncertainty, and associated difficulties in pricing. In the United States, this problem arises mostly with respect to crop and flood risks, although government flood insurance is limited to residential and very small commercial customers. There is ongoing tension between government and private-sector players

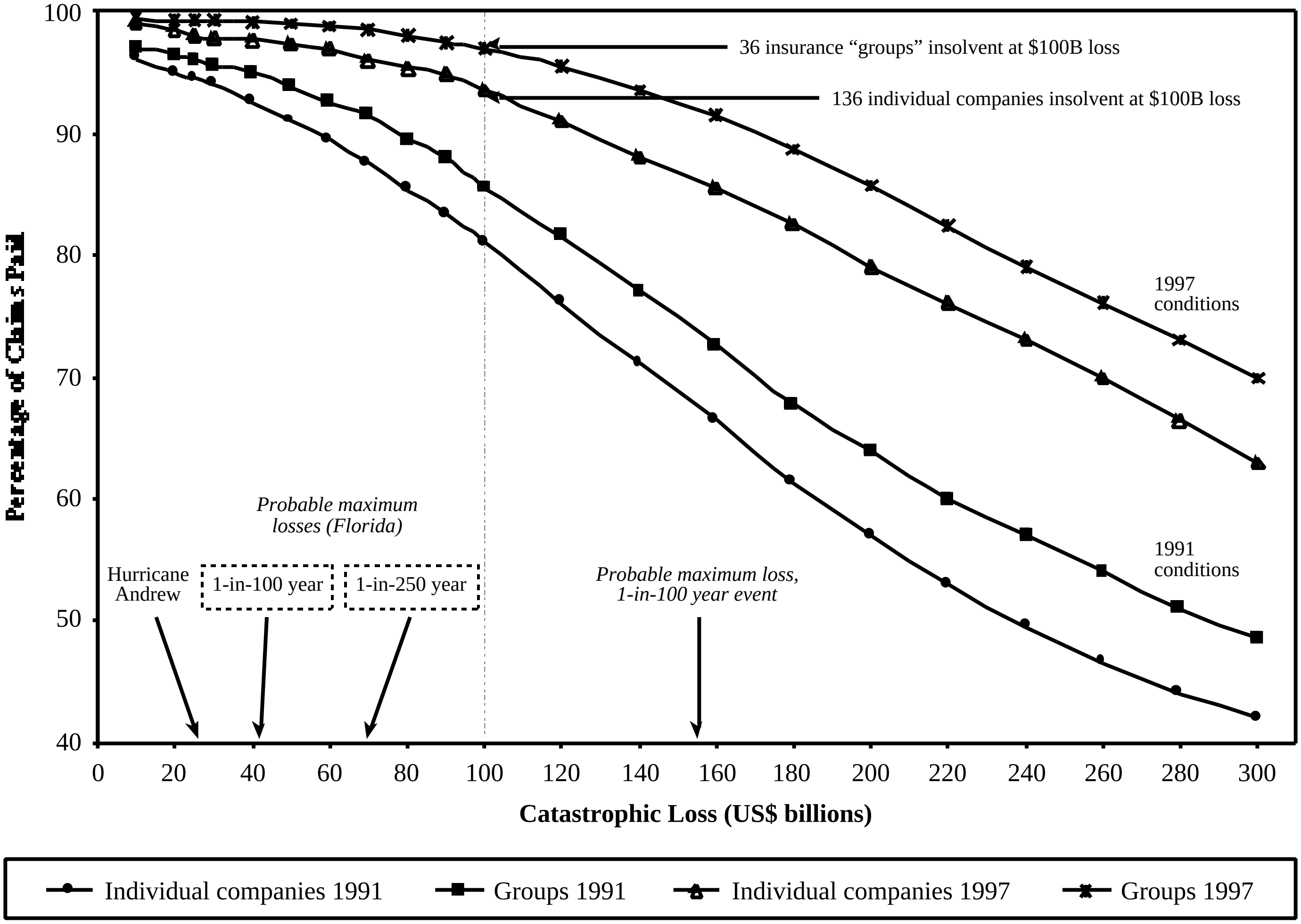

Figure 15-8: Reductions in claims payable, by size of loss. Ability of U.S. property-casualty insurance sector, as a whole, to pay claims over a wide range of losses. The chart shows four views, encompassing changes in capacity between 1991 and 1997 and whether companies have access to resources of groups that own them. Groups are not obligated to pay losses experienced by individual member firms but retain the option to do so. Together, these four scenarios represent a range of ability to pay losses. For example, for a US$155 billion loss year—a recent estimate of probable maximum loss (PML) (GAO, 2000) could be several events combined, including weather- and nonweather-related ones—65 to 90% of claims would be paid (adapted from Cummins *et al*., 1999). PML benchmarks are from GAO (2000).

in the natural disaster arena, with each looking to the other to clarify the somewhat ambiguous division of responsibility.

In Canada, government (federal, provincial, and municipal) has paid most of the natural disaster payments, amounting to US$15 billion (CDN$22 billion) in disaster relief between 1982 and 1999, including 86% of flood-related losses (Emergency Preparedness Canada, 2000). Consolidated data for U.S. government payments for natural disasters are not readily available. One source reports US$119 billion (1993US$) in government outlays between 1977 and 1993 (Anderson, 2000).

Government insurance programs can have difficulty achieving solvency, as exemplified by the US$810 million deficit in the U.S. flood insurance program in the mid-1990s (Anderson, 2000). U.S. crop and flood insurance programs have never been profitable, and growing coastal erosion risks will require doubling of rates in the United States (GAO, 2000; Heinz Center, 2000). Government insurance programs also have resulted in cases of maladaptation (e.g., inducing people to settle in vulnerable areas) (Heinz Center, 2000).

15.2.7.3 Creating and Maintaining Adaptive Capacity

Private and public insurers alike have at their disposal a variety of tools to increase adaptive capacity. These tools can be divided into the broad categories of risk spreading and risk reduction (see Chapter 8). Some of these strategies involve shifting of risk between the public and private spheres, or even back to the consumer, and in that regard have considerable public policy ramifications that are beyond the scope of this chapter.

Given their sensitivity and potential vulnerability to weather-related losses, North American insurers and their regulators have designed a variety of adaptation mechanisms. These strategies include economic measures—raising premiums or deductibles, withdrawing coverage, creating systems for pooling risks among multiple insurers (e.g., U.S. government-mandated FAIR Plans or beach/windstorm plans and state-mandated "guaranty funds" based on mandatory contributions of insurers, to pay the claims of insolvent insurers)—and the use of capital market alternatives to finance risk (see Chapter 8). Responses also include more engineering-oriented risk-reduction strategies, such as land-use planning, flood control, cloud seeding (see Section 15.3.2.4), and early warning systems.

Hurricane Andrew in 1992 and the 1998 ice storm (see Section 15.3.2.6) were wake-up calls for the North American insurance industry. Among the numerous responses have been increased utilization of catastrophe modeling, a more proactive stance toward disaster preparedness/recovery, new efforts in land-use planning, increased attention to building codes, and increased use of incentives to implement loss-prevention measures (Bruce *et al.*, 1999b).

One embedded vulnerability facing insurers and government risk managers alike is that, by design, their actuarial outlook and disaster reserving conventions are based on past experience. There is an emerging and encouraging trend to forward-looking catastrophe modeling, although it has yet to integrate knowledge from climate change modeling. Thus, under climate change, the potential for surprise is real. Vulnerability is compounded by the potential for changes in the frequency, variability, and/or spatial distribution of extreme weather events. Increased uncertainties of this nature can complicate and confound insurer methods for preparing for future events (Chichilnisky and Heal, 1998).

15.2.7.4 Equity and Sustainability Issues in Relation to Insurance

Although North America is a wealthy region, significant equity considerations arise from its cultural and economic diversity (Hooke, 2000). This raises important issues concerning the design and deployment of effective natural disaster preparedness programs (Solis *et al.*, 1997). Lower income groups tend to live in more vulnerable housing and are least able to afford potential increases in insurance costs by insurers or cross-subsidies utilized to spread risks (Miller *et al.*, 2000). Poorer individuals also tend to carry little if any life and health insurance and thus may be uninsured against public health risks such as urban heat catastrophes or urban air quality risks posed by climate change (see Chapter 9).

In some cases, sustainable development and environmental protection complement insurance loss reduction objectives. Examples include protection or restoration of wetland areas that increases tidal flooding defense, sustainable forest practices that reduce risk of inland flooding and mudslides, or agricultural practices that increase drought resistance or reduce soil erosion (see Chapters 5 and 8; Scott and Coustalin, 1995; Hamilton, 2000). Similarly on the end-user side, a variety of energy conservation and renewable energy measures have been found to offer insurance loss-control co-benefits (Mills, 1996, 1999; Nutter, 1996; Mills and Knoepfel, 1997; American Insurance Association, 1999; Vine *et al.*, 1999). The insurance sector itself has begun to examine its activities within the broader framework of sustainability (Mileti, 1997; Kunreuther and Roth, 1998).

15.3. Adaptation Potential and Vulnerability

15.3.1. Generic Issues

Subregions within North America can be affected by global climate change through direct first-order effects on land and water resources and through indirect impacts that are related to reactive and proactive responses by actors within and outside the subregion. Direct effects include incremental processes and extreme weather events with long-term impact on the region's environmental, social, or economic systems. Indirect effects would include societal changes that could be set in motion, primarily by policies generated outside the region, to mitigate greenhouse warming or adapt to perceived threats.

Calculations of climate-related impacts within subregions must consider both direct and indirect effects. Actual impacts will depend on the effectiveness of adaptation. For example, changes in growing season, natural streamflow, or climate-related demand for heating and cooling energy can be calculated directly from changes in climatic parameters. However, changes in potential may not necessarily lead to a response by stakeholders. Other factors may intervene to prevent a subregion from adapting to a new climate-related opportunity or risk, including changes in market conditions, institutional arrangements, and management objectives.

Because North America includes areas of intensive urban and landscape management, as well as areas of "extensive" management, adaptation capabilities and vulnerabilities are likely to vary between subregions. There is potential for maladaptation, in part as a result of the availability of insurance and disaster relief measures (MacIver, 1998). Vulnerabilities also exist in highly developed regions with well-maintained infrastructure (e.g., dams designed for flood control) because of the growing need to manage resources to achieve multiple objectives. Would climate change ameliorate or exacerbate these risks? Analysis of case studies can provide guidance.

15.3.2. Subregional and Extra-Regional Cases

15.3.2.1. Introduction

The discussion that follows offers a sample of subregional and extra-regional cases that reflect the unique and changing nature of the relationship between climate and places in the North American context. Six subregions have been defined: Pacific, Rocky Mountains–Southwest United States, Prairies–Great Plains, Great Lakes–St. Lawrence, North Atlantic, and Southeast United States (see Figure 15-9). These subregions represent unique landscapes that have experienced development paths that reflect natural potential for resource development as well as region-specific histories of evolving economies and communities. Some of these cases describe responses to recent extreme events. Others focus on scenarios of future climatic changes. Canada and the United States have a long history of cooperating on resource management concerns in transboundary areas, including the Boundary Waters Treaty of 1909 and more recent agreements on transboundary air pollution, watershed development, and the environmental agreement associated with NAFTA. There also have been binational and subregional conflicts over a wide range of issues that are climate-sensitive, including water resources, wetland protection, trading of forest and agricultural commodities, and harvesting of transboundary fish stocks. Various cooperative management approaches are being considered. Could climate change make a difference in any of these conflicts? Extra-regional issues are considered for the Arctic, U.S.-Mexican, and U.S.-Caribbean borders.

15.3.2.2. Pacific Subregion

This subregion includes the Columbia River basin—the fourth-largest in North America, and one of the most valuable and heavily developed watersheds. The Columbia system produces 18,500 MW of hydroelectricity; it also is managed for flood control, agriculture, navigation, sport and commercial fisheries, log transportation, recreation, wildlife habitat, and urban, industrial, and aboriginal uses. Climate variability affects the total volume and temporal pattern of natural runoff, although binational management agreements have substantially altered this pattern. Any hydrological changes caused by long-term climatic change will have impacts that may affect the management of the system and the nature of conflicts among various users.

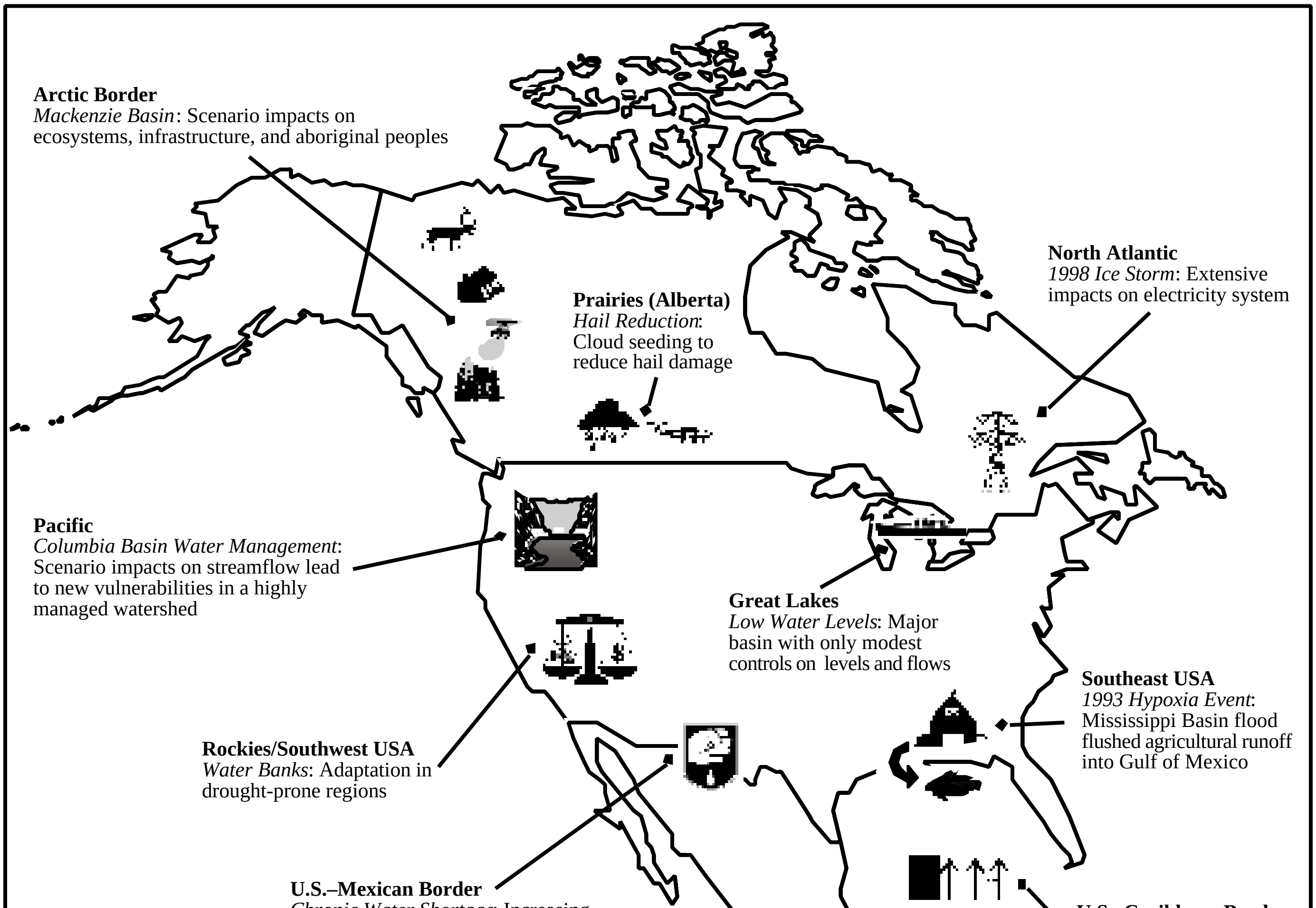

Figure 15-9: Subregional cases from North America (described in Section 15.3.2).

Recent management and policy changes have led to changes in system operations; fish habitat protection now is regarded as a high priority—on par with hydroelectricity production and flood control (Cohen *et al*., 2000).

Climatic change is expected to lead to reductions in annual streamflow. Estimates for three warming scenarios range from a small increase to a decrease of 16% by 2050, with an earlier annual peak, higher winter flows, and lower summer flows (Lettenmaier *et al*., 1996, 1999; Hamlet and Lettenmaier, 1999; Miles *et al*., 2000). This would affect system reliability. Results from a reservoir system model for the driest of the three scenarios [based on the Max Planck Institute (MPI) GCM, ECHAM-4] indicate reductions of 15% in reliability for Snake River irrigation, 11% for McNary Dam "biological flow" (to support fish habitat), 14% for firm energy production, and 19% for nonfirm energy production. Reliability for flood control would remain relatively unchanged in this case but would decrease in the wetter scenarios (Hamlet and Lettenmaier, 1999; Miles *et al.*, 2000).

Interviews were held in 1997 with water resources managers and other stakeholders in the upstream portion of the Columbia, on the Canadian side. Their responses to the MPI scenario were similar to those obtained from the reservoir system model. For example, they noted that flood risk would not necessarily be reduced because upstream storage facilities may be releasing high discharges for fish habitat protection or other reasons. Similarly, irrigation supply and hydroelectricity production would be reduced because of lower annual flow combined with fish protection requirements. In these circumstances, regional utilities might have to purchase electricity from fossil fuel sources, thereby affecting the region's ability to meet GHG emission targets (Cohen *et al.*, 2000).

This case study suggests that despite the high level of development and management in the Columbia basin, vulnerabilities would still exist and impacts could still occur in scenarios of natural streamflow changes caused by global climate change. It also suggests that expanded development of hydroelectric facilities, as a means of reducing GHG emissions, will create considerable challenges to management, given increases in the sensitivity of regional energy supplies and other water-related resources to climate.

15.3.2.3. Rocky Mountains–Southwest U.S. Subregion

Rapid population growth coupled with water supplies that are limited, heavily utilized, and highly variable present significant challenges to governments and the private sector in this region. The effects of climate change may add further stresses (Frederick and Schwarz, 1999). One strategy that has been developed to cope with these issues is use of water banks. Water banks can be used to mitigate the economic impacts of drought periods by increasing the reliability of water supply or by facilitating short-term reallocation of water among users. Water banks can be used for environmental purposes—for example, Idaho's water banks have provided significant quantities of water to assist anadromous fish passage (Miller, 2000b). However, to the extent that water banking entails increased water withdrawals from surface sources, there could be further adverse impacts on aquatic ecosystems.

There are two types of arrangements to which the term "water bank" has been applied. "Groundwater storage banks" include active conjunctive-use programs whereby surface water is used to recharge an aquifer, which is then used as a source of water supply during periods when surface water is less abundant. Another use of the term "water bank" refers to a formal mechanism created to facilitate voluntary changes in the use of water under existing rights. We can distinguish these as "water transfer banks." The defining feature of this type of water bank is that it provides an established process or procedure for accomplishing such transfers. California has pioneered the development of both types of water banks. Various groundwater recharge programs have been developed in California, some of which incorporate features of groundwater banks and water transfer banks. One such example, the Bakersfield Recharge Facility in Kern County, is discussed below. The Emergency Drought Water Banks set up by the state of California in 1991, 1992, and 1994 are examples of water transfer banks.

In 1987, at the beginning of a severe multi-year drought, California had relatively little experience with privately arranged water transfers outside the confines of individual irrigation districts and major project service areas. The lack of market development may have been related, in part, to the predominance of large state and federal water projects in California and, in part, to the difficulty of obtaining approval for such transfers from the California State Water Resources Control Board (SWRCB) (MacDonnell, 1990; NRC, 1992). As the drought persisted, it became clear that neither within-project water transfers nor those requiring approval of the SWRCB were likely to occur in sufficient volume to alleviate the very uneven impacts of the drought on major urban centers and irrigated agriculture. In 1991, the state responded to the growing crisis by creating the first Emergency Drought Water Bank. California's Department of Water Resources (DWR) acted as the manager of these water banks because most of the anticipated transfers required conveyance of the water through State Water Project (SWP) facilities (primarily the state's pumping plant in the Sacramento/San Joaquin delta and the California aqueduct). DWR personnel negotiated the purchase contracts, monitored compliance with those contracts, obtained SWRCB approval where needed, and coordinated deliveries of water to purchasers. Despite initial difficulties in estimating the quantity of water needed and the appropriate price, as well as some concerns about uncompensated third-party impacts, the program generally is considered to have been a major success—with net economic benefits far exceeding any negative impacts (Howitt *et al.*, 1992; Dixon *et al.*, 1993; MacDonnell *et al.*, 1994).

Another successful California water bank is the 1,135-ha recharge facility operated by the city of Bakersfield. This groundwater-banking program also facilitates water transfers.

The city owns Kern River water rights, which yield a highly variable quantity of water from 1 year to the next. A portion of these rights is leased on long-term contracts to neighboring irrigation districts. The city has constructed a recharge facility into which it spreads much of its remaining Kern River water. This activity has increased the amount of water that potentially is available for extraction in the underlying aquifer. Three other water districts also are allowed to bank their surplus water by spreading it in the recharge facility. Each bank participant can withdraw the water in its own account, as needed (e.g., during drought periods), or transfer the water to another party:

> "The banked water can be extracted and transported for direct use, sold or exchanged, with the stipulation that extracted water must be used in the San Joaquin Valley portion of Kern County for irrigation, light commercial and industrial, and municipal or domestic purposes, unless otherwise specified. Located upstream of the facility, the city of Bakersfield often sells its banked water to users downstream, or exchanges it for water from other sources" (Wong, 1999).

Operation of this recharge facility provides county water users with drought insurance and flood control benefits. "Banking recharge operations during flood release periods serve to minimize downstream flooding problems while maximizing recharge of water on the Kern River for local benefit" (Wong, 1999). For example, the bank participants successfully used the recharge facility in 1995 to manage heavy runoff.

15.3.2.4. Prairies–Great Plains Subregion

An attempt at proactive "mitigation" of an atmospheric threat is the cloud seeding program underway in Alberta since 1996 to reduce the severity of hailstorms. Central North America is one of the most hail-prone regions in the world. A 1995 hailstorm did more than US$1.1 billion damage in Dallas, a 1990 storm did US$600 million damage in Denver, and a 1991 hailstorm did about US$240 million (CDN$340 million) damage in Calgary. Hailstorms account for more than half of the catastrophic events in this region. In the Alberta program, storms with the potential to generate hail damage are intensively treated through cloud seeding. Since the program began, there has been an increase in the number of potential hailstorms, yet a pronounced reduction in actual hail damage. Indeed, during the first 4 years of the program, only one storm has done damage in the area under supervision (IBC, 2000).

Throughout the long history of hail suppression in North America and elsewhere, success has been mixed (e.g., Changnon *et al.*, 1978), so it is not yet clear whether this approach will work over the long term. The experimental program in Alberta is expected to continue indefinitely because the modest US$1 million (CDN$1.5 million) annual operating cost appears to be more than offset by the reduction in observed hail damage (IBC, 2000).

15.3.2.5. Great Lakes–St. Lawrence Subregion

Scenario-based studies in the Great Lakes–St. Lawrence basin conducted over the past 15 years (see Section 15.2.1) have indicated consistently that a warmer climate would lead to reductions in water supply and lake levels (Cohen, 1986; Croley, 1990; Hartmann, 1990; Mortsch and Quinn, 1996; Mortsch, 1998). Observed low-level events have been rare during the past several decades, but when they have occurred (e.g., 1963–1965, 1988), conflicts related to existing water diversions and competing stakeholders have led to legal challenges and political stress (Changnon and Glantz, 1996).

In 1998–1999, dry and record warm weather combined to reduce ice extent and lower water levels (Assel *et al.*, 2000). In November 1998 and again in spring 1999, cargo limits were placed on ships travelling through the Great Lakes and the St. Lawrence Seaway when water levels fell by more than 25 cm. Some commercial ships ran aground. Lower water levels significantly increased the distance between docks and waters at some tourism facilities and marinas. Recreational boaters had access to fewer waterways. In addition, hydroelectric facilities are very dependent on water flows and have expressed concern about maintaining production (Mittelstaedt, 1999). These observed impacts are similar to the impact scenarios described earlier. The reduction in ice cover did provide some offsetting benefits by reducing the need for icebreakers during the winter and spring (Assel *et al.*, 2000).

Water resources management, ecosystem and land management, and health concerns are highlighted in the Great Lakes–St. Lawrence Basin Project (GLSLB) and the Toronto–Niagara Region Study (TNR). The former is a binational exercise that used analogs and model-based scenarios to assess impacts and adaptation responses. Reduced lake levels continue to be projected, leading to potential conflicts over water regulation and diversions, water quality, and rural water use (Mortsch *et al.*, 1998). The TNR exercise is in its initial stages. Within the GLSLB region, the TNR represents a highly urbanized area that has a significant impact on surrounding agricultural and forest landscapes. Urban influences on land use, air quality, and human health will be a major focus. In addition, concerns about vulnerabilities of the built environment (transportation and energy infrastructure, etc.) have been identified as high-priority research questions (Mills and Craig, 1999).

There also have been studies of alternative scenarios for lake-level management. Decision support systems can facilitate this process (Chao *et al.*, 1999).

15.3.2.6. North Atlantic Subregion

Severe winter storms combined with a loss of power can have devastating consequences, even in a highly developed region such as Ontario-Quebec and the northeast United States. In January 1998, a severe winter storm struck; instead of snow, some areas accumulated more than 80 mm of freezing rain—double the

***Table 15-5**: Estimated damages from 1998 ice storm.*[a]

Type of Loss	Canada (CDN$)	United States (US$)	Total (US$)
Insured losses	$1.44 billion	$0.2 billion	$1.2 billion
Insurance claims	696,590	139,650	835,240
Deaths	28	17	45
People (customers) without power	4,700,000 (1,673,000)	546,000	5,246,000
Electricity transmission towers/distribution poles toppled	130/30,000	unknown	unknown
Electric transmission system damage	$1 billion	unknown	unknown
Manufacturing, transportation, communications, and retail business losses	$1.6 billion	unknown	unknown
Forests damaged	unknown	17.5 million acres	unknown
Loss of worker income	$1 billion	unknown	unknown
Dairy producers experiencing business disruption	5,500	unknown	unknown
Loss of milk	$7.3 million	$12.7 million	$18 million
Agricultural sector (poultry, livestock, maple syrup)	$25 million	$10.5 million	$28 million
Quebec and Ontario governments	$1.1 billion		

[a] Based on analysis conducted by the Canadian Institute for Catastrophic Loss Reduction and U.S.-based Institute for Business and Home Safety, both of which are insurance industry organizations (Lecomte *et al*., 1998). Losses as of 1 October 1998 (1 CDN$ = 0.7 US$).

amount of precipitation experienced in any prior ice storm. The result was a catastrophe that produced the largest estimated insured loss in the history of Canada. The same storm ran across northern New York and parts of Vermont, New Hampshire, and Maine in the United States (see Table 15-5). The basic electric power infrastructure, with its lengthy transmission lines, was severely damaged, stranding some residents and farmers without power for as many as 4 weeks. Almost 5 million people were without power at some point during the storm, and consideration was given to evacuation of Montreal. In Canada, there were 28 deaths, and damages were US$2–3 billion (CDN$3–4 billion) (Kovacs, 1998; Kerry *et al.*, 1999). The same storm caused 17 deaths in the United States, as well as damages exceeding US$1 billion in New York and the New England states—one-third of which was from losses to electric utilities and communications (DeGaetano, 2000). Combined Canadian and U.S. insured losses stood in excess of US$1.2 billion as of October 1, 1998. Total Canadian insured and uninsured economic losses were approximately US$4 billion (CDN$6.4 billion).

The ice storm produced more than 835,000 insurance claims from policyholders in Canada and the United States. This was 20% more claims than were created by Hurricane Andrew, the costliest natural disaster in the history of the United States.

The event served as a grim learning laboratory for the insurance and disaster recovery communities. It revealed the wide spectrum of insured and noninsured losses that can materialize from a single natural catastrophe, including:

- Property losses (e.g., roof damages and destruction of perishable goods as a result of loss of electric power)
- Business interruption losses (19% of the employed Canadian workforce was unable to get to work)
- Health/life losses (including losses incurred during recovery operations)
- Additional living expense costs for people relocated to temporary housing
- A host of agricultural losses, ranging from livestock deaths, to interrupted maple syrup production, to milk production
- Disruption and damage to recreation and tourism infrastructure

- Disaster recovery costs, including personnel and overtime expenses, provision of backup electric generators and fuel, debris clearing, temporary shelter for displaced citizens, and disaster assistance payments to victims.

Ice storms occur regularly in North America, although severe and prolonged damage is rare. Several urban centers are vulnerable to major storms, including Minneapolis, Winnipeg, Chicago, Detroit, Toronto, Buffalo, Montreal, Boston, and even New York. Many communities are not prepared for an extreme winter storm, particularly combined with the loss of electric power. In the 1998 storm, total losses exceeded insured losses by a substantial margin. The event also raised questions about the connection between such events, the El Niño phenomenon, and global climate change.

15.3.2.7. Southeast United States

The Gulf of Mexico has a problem with hypoxia (low oxygen) during summer over an area of approximately 15,000 km^2 (Turner and Rabalais, 1991; Rabalais *et al*., 1996). The hypoxia has been shown to be a result of excess nutrients—primarily nitrogen—transported to the Gulf from the Mississippi River basin. This basin is heavily fertilized for crop production. The causes of, and proposed solutions for, this hypoxia problem are an excellent example of a complex interaction between climate and other human stresses on natural ecosystems. Specific "lessons" from this problem include the following:

- The hypoxia problem was greatly exacerbated by the 1993 Mississippi basin flood that appeared to "flush" large amounts of residual nitrogen from agriculture to the Gulf (Rabalais *et al*., 1996). Increases in extreme precipitation events, which are likely to occur with climate change, are likely to exacerbate coastal eutrophication problems in many locations.
- Recommended solutions to the hypoxia problem include creation of approximately 60,000 km^2 of wetlands to remove ~1,000 t yr^{-1} of nitrogen by denitrification (Mitsch *et al*., 2001). If such "eco-technologies" become a common solution to eutrophication problems on a global basis, they could result in a significant flux of N_2O to the atmosphere.

Management practices designed to reduce nitrogen losses from agricultural watersheds—from improved fertilizer management to the construction of wetlands—will be strongly affected by climate (NRC, 1993). Climate change will decrease the reliability of these practices. Increases in climate extremes almost certainly will decrease their long-term performance.

15.3.2.8. Arctic Border

Acase study of the regional impacts of climate change scenarios has been completed in the Mackenzie basin, a watershed that extends from the mid-latitudes to the subarctic in northwest Canada. A lengthy description of this case study, known as the Mackenzie Basin Impact Study, is available in Cohen (1994, 1996, 1997a,b,c). A sketch of the MBIS integrating framework is shown in Figure 15-10. Within this process, several types of integration exercises were used, including models, stakeholder consultation, and thematic discussions.

As a high-latitude watershed, the Mackenzie basin has been regarded as an area that might benefit in certain ways from a warmer climate. Taken individually, economic impacts could be quantified, and these impacts might show substantial benefits for the region. Other factors must be considered, however, and some of these factors may constrain the potential benefits:

- The current system of land transportation, much of which is based on a stable ice and snow cover for winter roads
- Current ranges and habitats of wildlife, which underpin conservation plans and native land claims
- Scientific uncertainty, which hampers anticipatory responses to projected beneficial conditions.

Potential negative impacts of climate warming also must be considered because they may offset possible benefits. An example is the implication of hydrological and landscape changes on water management agreements. Initial projections of runoff and lake levels are for declines below observed minima (Soulis *et al*., 1994; Kerr, 1997). Peace River ice cover will be affected by temperature changes and changes in outflow from the Bennett Dam in northeast British Columbia (Andres, 1994). There continue to be uncertainties in projections of hydrological impacts; the Global Energy and Water Cycle Experiment (GEWEX) is addressing these uncertainties (see Chapter 16). There has been a strong warming trend in the region during the past 40 years, and Great Slave Lake experienced new record minimum lake levels in 1995.

It would appear that the other main threats to the Mackenzie landscape are accelerated erosion and landslides caused by permafrost thaw and extreme events (fire, storm surges), especially in sloping terrain and the Beaufort Sea coastal zone (Aylsworth and Egginton, 1994; Solomon, 1994; Aylsworth and Duk-Rodkin, 1997; Dyke *et al*., 1997); increased fire hazard (Hartley and Marshall, 1997; Kadonaga, 1997); changes in climate conditions that influence the development of peatlands (Nicholson *et al*., 1996, 1997; Gignac *et al*., 1998); and invasion of new pests and diseases from warmer regions (Sieben *et al*., 1997).

Impacts on fisheries and wildlife are difficult to project, as a result of lack of long-term data, complexity of life cycles, and incomplete information on responses to previous environmental changes (Brotton and Wall, 1997; Gratto-Trevor, 1997; Latour and MacLean, 1997; Maarouf and Boyd, 1997; Melville, 1997). Outside of MBIS, there have been few impact studies on North American boreal and Arctic freshwater fisheries (Weatherhead and Morseth, 1998). Some information is available on terrestrial wildlife and Arctic marine fisheries (see Chapter 16). Others have outlined the potential for freshwater ecosystem

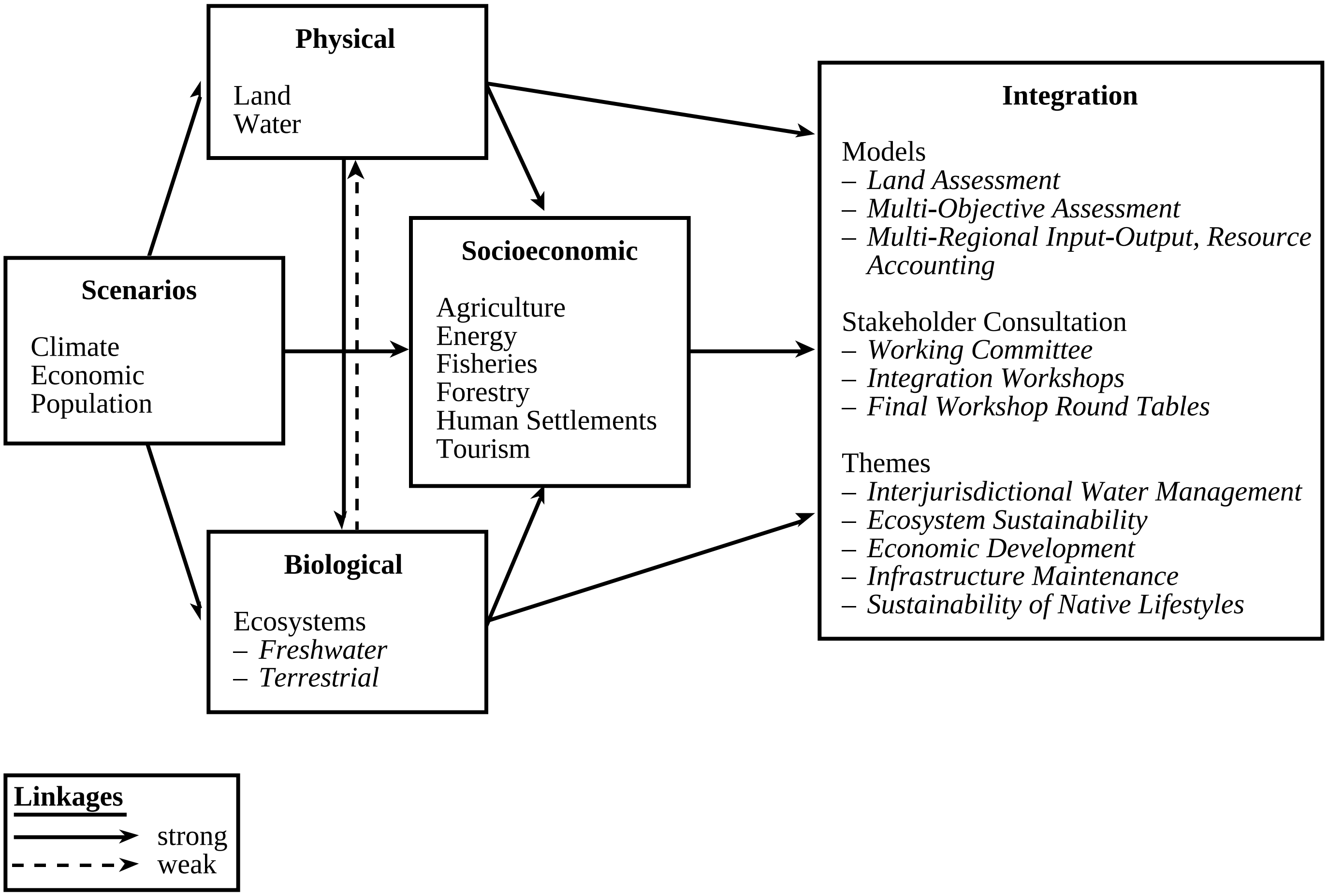

Figure 15-10: Research framework for MBIS (Cohen, 1997b). Scenarios were generated for use by physical and biological system studies. Socioeconomic component used results from these assessments, as well as climate scenario information where appropriate. Integration exercises were based on outputs from sectoral studies.

impacts, including loss or reduction of deltaic lakes, increased pondwater temperatures, side effects of permafrost thaw (including sedimentation of rivers), and changes in primary productivity depending on nutrient levels (Rouse *et al.*, 1997; Schindler *et al.*, 1997; Meyer *et al.*, 1999).

First-order and second-order impacts eventually lead to others that are considerably more difficult to address. Will land claims or water resources agreements be affected? Would it be appropriate to artificially maintain historic water levels in the Peace-Athabasca delta within this scenario of climate change (see Chapter 16)? Could there be new conflicts over land use, especially if agriculture expands northward to take advantage of improved soil capability to support crop production (Brklacich *et al.*, 1996, 1997b)? What might be the effects on parks and other protected areas (Pollard and Benton, 1994) and tourism (Staple and Wall, 1996; Brotton and Wall, 1997; Brotton *et al.*, 1997; Wall, 1998a,b)? Could climate change affect the economics of commercial forestry (Rothman and Herbert, 1997) or oil and gas production in the Beaufort Sea (Anderson and DiFrancesco, 1997)?

Two exercises dealt with individual perceptions of aboriginal responses to future scenarios. The first asked for a listing of physical and biological impacts, as well as how aboriginal people would be affected if they continued to pursue a traditional aboriginal lifestyle or if they became more active in the formal wage economy (similar to the dual-economy situation described by Shukla, 1997). Results showed that perceptions of impact and vulnerability were influenced by visions of future lifestyles (Aharonian, 1994). The second exercise used input-output modeling and a community survey to look at responses to a potential benefit of warming—an opportunity for expanded activity in the formal wage economy (because of the longer summer) that would force people to relocate from their traditional community if they wanted the employment. Results showed a willingness to accept the opportunity, but there were concerns about social impacts on the community of relocation or creation of commuter workers who would be absent for extended periods (Lonergan and Kavanagh, 1997).

Potential land-use impacts and adaptation responses also were considered. One issue was whether the region could take advantage of a longer growing season to expand wheat production. Results showed that this was possible (given the constraints of the model), but only if expanded irrigation services would be made available (Brklacich *et al.*, 1997a). The side effects of this are unknown. The second case was a forestry study that showed that commercial yields of softwood lumber would decline because of changing growth potential for these species, combined with increased fire frequency. This would offset improvements for hardwood species (Hartley and Marshall, 1997; Rothman and Herbert, 1997). Integrated modeling exercises, using these sectoral outputs, indicated that agriculture production would be able to achieve its goals, but there would be shortfalls in softwood (spruce) production and a substantial increase in erosion (Yin and Cohen, 1994; Huang *et al.*, 1998; Yin *et al.*, 2000).

Stakeholders were asked to react to the various research results through thematic roundtable discussions. One of these themes was infrastructure maintenance. Engineers suggested that physical infrastructure—such as roads, airstrips, and pipelines—could be repaired or designed differently to meet changing climatic conditions, but there certainly would be increased costs in doing so. It also was suggested that the notion of infrastructure should include education and insurance mechanisms, emergency response, and social and cultural institutions that pool risk and support people in times of stress (Zdan, 1997). Changes in community development already have influenced emergency response to floods and could affect adaptation to future climate changes (Newton, 1995, 1997).

In another thematic context—ecosystem sustainability—it is unclear whether current institutions in the region would be capable of coping with a scenario of simultaneous changes in renewable resources and dependent communities, superimposed on other nonclimate stresses affecting the region. During the past few years in northern Canada, co-management processes have been developing for aboriginal and non-aboriginal (and government) stakeholders concerned with wildlife and water resources. This has been part of a larger trend of devolution of responsibility from central to regional authorities in Canada—a trend that is taking place for reasons other than climate change. Regional stakeholders regard these processes as their best approach to coping with climate change, although it was noted that climate change would be a new experience for everyone (Irlbacher, 1997).

Climate change joins a long list of factors that affect the lifestyles and livelihoods of people who live in the north. With or without climate change, however, native lifestyles are in flux, and any potential impacts should be considered in that context. Communities already are being affected by changes in wildlife harvesting opportunities and wage-based employment. Education and transportation have improved, and some native people are opting for jobs in the wage economy. As the "two economies" continue to evolve, communities will be trying to provide opportunities in traditional and wage-based activities, but if climate change affects wildlife numbers or habitats, traditional patterns of wildlife harvesting would have to be modified.

Native people have adapted to change, but the predictability of the extent, duration, and speed made such adaptation possible. There is real concern that if future changes were to be fast, dramatic, and surprising, native communities would be left in a very vulnerable position. Traditional lifestyles would be at risk of disappearing.

Stakeholders have proposed that monitoring and adaptation could be undertaken through more effective partnerships between governments and native communities. Traditional knowledge, along with western science, should be used in modern management practices as well as in traditional activities. Training in renewable resource management for aboriginal youth would be an important component of preparing for the future (Pinter, 1997).

15.3.2.9. U.S.–Mexican Border

The U.S.-Mexican border is characterized by a semi-arid climate, with higher precipitation toward both coasts. Evaporation exceeds precipitation for many months of the year, causing a soil moisture deficit. Many studies relate climate and hydrology along the U.S. border states (Green and Sellers, 1964; Hastings and Turner, 1965; Norwine, 1978; Cayan and Peterson, 1989) and along the Mexican border states (Mosiño and García, 1973; Schmidt, 1975; Acosta, 1988; Cavazos, 1998). The western border has an annual rainfall of about 250 mm yr^{-1}, with temperatures ranging from 10 to 28°C. The Arizona-Sonora border has a much more extreme and desert climate, with only 80 mm yr^{1} of precipitation and maximum temperatures reaching 45°C. Around the Ciudad Juarez (Mexico)–El Paso (Texas) border, annual precipitation is around 220 mm, with maximum temperatures reaching 40°C. Finally, in the easternmost part of the border (Brownsville, Texas–Matamoros, Mexico), annual precipitation is close to 675 mm, with temperatures ranging from 11 to 38°C.

There is large climate variability along the U.S.–Mexican border states. Drought and floods occur frequently (Powell Consortium, 1995), some influenced by the occurrence of El Niño (Cavazos and Hastenrath, 1990; Cayan and Webb, 1992). The Mexican states along the border are highly vulnerable to drought, particularly along the Rio Grande region, areas with low precipitation rates (less then a 100 mm yr^{-1}) (Mundo and Martínez Austria, 1993; Hernández, 1995; Mendoza *et al.*, 1997). Strong El Niño events during the summer result in severe water deficit in northern Mexico (Magaña and Quintanar, 1997), and serious negative impacts in agricultural activities. Such vulnerable conditions during drought periods have resulted in legal disputes between Mexico and the state of Texas with regard to rights to Rio Grande water.

It is unclear what the signs of future changes in precipitation and water availability will be along the border (Mearns *et al.*, 1995; Magaña *et al.*, 1997; Mendoza *et al.*, 1997). Some scenarios suggest increased winter precipitation and decreased summer precipitation (Magaña *et al.*, 1998). Without reliable predictions of precipitation changes across drainage basins, little confidence can be placed in hypothesized effects of global warming on annual runoff (Karl and Riebsame, 1989).

Therefore, to examine potential impacts of climate change on water availability, most studies make use of long instrumental records of precipitation and streamflow. Some analyses indicate that in recent decades there is a positive trend in streamflow and even precipitation, corresponding to more water availability along the U.S.–Mexican border (Magaña *et al.*, 1998; Magaña and Conde, 2000). However, demand for water in agriculture, industries, and cities is increasing steadily, surpassing recent increases in water availability (Mundo and Martínez Austria, 1994).

The signal of climate change along the U.S.–Mexican border may be exacerbated along the Mexican side by differences in land use. Along the U.S. side, the presence of gardens and green areas lead to a cooler environment relative to the Mexican side. Currently, maximum temperatures in contiguous border towns may differ by as much as 3°C as a result of different characteristics in vegetation (Balling, 1988). This cross-border contrast is possible because water consumption in U.S. border cities is four times larger than in Mexican border cities. Surface water distribution along the border (Rio Grande and Colorado watersheds) is regulated by the Binational Treaty of 1944. Yet, there are no regulations for subsurface water (Sanchez, 1994).

15.3.2.10.The U.S.–Caribbean Border

Some of the U.S.–Caribbean border problems that may increase as a result of climate change are related to:

- Effects of sea-level changes on coastal ecosystems
- Effects of temperature increases on terrestrial and aquatic ecosystems, including possible effects on economically important species
- Effects of climate change on socioeconomic structures and activities.

Considering the high population density in part of the Caribbean islands and coastal areas, human settlements will be highly affected by sea-level rise and saline intrusion (Vincente *et al.*, 1993). Coral reefs in the region may be severely affected by coral bleaching induced by warmer water temperatures (Milliman, 1993).

Tourism is a major economic activity in most of the region. A change in rainfall patterns, tropical storms, and warming of the climate in temperate countries may affect the comparative advantages of this sector in the region (Alm *et al*., 1993). Narrow beaches combined with projected sea-level rise contribute to the vulnerability of the tourism sector to changes in climate (Gable, 1997).

Potential consequences of changes in extreme events (e.g., hurricanes) are not well-defined. Other trends, such as changing demographic patterns, may exacerbate impacts. Recent large losses of life from rainfall-induced floods, mudflows, and landslides reflect increasing concentrations of residents in high risk areas (Rodriguez, 1997; Pulwarty, 1998).

15.4. Synthesis

Our impacts and adaptation assessment indicates that changing climate and changing patterns of regional development have challenged North America and will continue to do so. Damage costs from recent climatic events have increased, and conflicts over climate-sensitive resources (e.g., fish) continue to occur. Future climatic changes may exacerbate these problems and indeed create new ones. Opportunities may arise from a warming climate, and some innovative adaptation mechanisms (e.g., water banks) are being tested to address current problems. However, the literature provides few cases on how adaptive strategies could be implemented in the future as regional climates continue to change.

Recent studies in agriculture point to greater crop diversity and possibilities for adaptation as factors in reducing estimates of future damage. Production forestry is regarded in much the same way, except in high-latitude regions where vulnerabilities to changing climate-related risks (pests, fire, permafrost thaw) still are considered significant challenges for management. Estimates of future damage to U.S. coastal zones have declined despite the recent series of high-cost extreme events. However, studies also have documented changing vulnerabilities of built (urban) environments to atmospheric events, risks to indigenous lifestyles, and the challenge of managing resources within a changing climatic regime to meet multiple objectives. Climate change along the U.S.–Mexican border may result in social and economic problems related to transboundary water resources. Unique natural ecosystems such as prairie wetlands, alpine tundra, and coldwater ecosystems are at risk, and effective mitigation is unlikely.

As impact studies of North America attempt to include adaptation in a more significant way, damage estimates in some sectors decline or become benefits. Mendelsohn and Neumann (1999) illustrate this trend for agriculture, production forestry, and coastal zone impacts in the United States. What also emerges, however, is that high damage costs are still calculated for water-related activities and summer energy demand. Most important, there are several outstanding methodological issues related to the evolution of economic activities, adaptation assumptions, and the value of nonmarket components, resulting in continued difficulties in estimating the cost of impacts and the costs and benefits of adaptation responses. If optimistic views about adaptation were realistic, North America should have been better able to plan for extreme events. Recent experience demonstrates high capability in emergency response, but long-term problems remain.

During recent extreme weather events, synergies between development pressures and environmental changes have resulted in substantial damages. Examples documented in Sections 15.2.1, 15.2.3, 15.2.7, and 15.3.2 include water-quality problems resulting from North Carolina hurricanes, damage from the 1998 ice storm, reductions in fish stocks as a result of climatic shifts combined with fishing pressure, and various impacts

***Table 15-6**: Climate change adaptation issues in North American subregions. Unique issues for certain locations also are indicated.*

North American Subregions	Development Context	Climate Change Adaptation Options and Challenges
Most or all subregions	– Changing commodity markets – Intensive water resources development over large areas—domestic and transboundary – Lengthy entitlement/land claim/treaty agreements—domestic and transboundary – Urban expansion – Transportation expansion	– Role of water/environmental markets – Changing design and operations of water and energy systems – New technology/practices in agriculture and forestry – Protection of threatened ecosystems or adaptation to new landscapes – Increased role for summer (warm weather) tourism – Risks to water quality from extreme events – Managing community health for changing risk factors – Changing roles of public emergency assistance and private insurance
Arctic border	– Winter transport system – Indigenous lifestyles	– Design for changing permafrost and ice conditions – Role of two economies and co-management bodies
Coastal regions	– Declines in some commercial marine resources (cod, salmon) – Intensive coastal zone development	– Aquaculture, habitat protection, fleet reductions – Coastal zone planning in high-demand areas
Great Lakes	– Sensitivity to lake-level fluctuations	– Managing for reduction in mean levels without increased shoreline encroachment

from recent water-level fluctuations in the Great Lakes. Unfortunately, only a few climate change scenario studies explore these kinds of synergies. Besides the challenge of projecting future economies, scenario studies of impacts and adaptation also have to consider the varied demands of regional stakeholders from the same resource and/or location. A summary of adaptation issues for North American subregions is provided in Table 15-6.

A wide range of factors—including changing political and institutional arrangements, technologies, and perceptions—may influence regional development futures. Concerns about development, equity, and sustainability are emerging in international negotiations of the United Nations Framework Convention on Climate Change and the Kyoto Protocol, and regional impacts/adaptation concerns can play an important role in this debate (Munasinghe and Swart, 2000). How could development paths alter a region's vulnerability to climate change? Could incentives related to emission reduction also enhance adaptation? Or, could management for certain environmental objectives lead to difficulties in meeting others? The example from the Columbia basin (Section 15.3.2), in which managing for fish protection could lead to increases in GHG emissions (Cohen *et al*., 2000), illustrates the dilemma that many subregions could face as they consider options for responding to climate change scenarios. How can these interactions be addressed in scenario studies? How can the various economic and social dimensions be accounted for so that there could be more confidence in estimates of impacts damages and adaptation costs/benefits?

Additional information on alternative climate scenarios and regional development futures will be needed in order to improve estimates of the costs of subregional impacts of climate change and the costs and benefits of adaptation responses. As measures associated with the Kyoto Protocol attract more attention from governments and industries, consideration also should be directed at studies on the interplay of mitigation and adaptation at the subregional scale.

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