Overview: Assessing the Impacts of Climate Change on U.S. Forests

Linda A. Joyce, USDA Forest Service, Rocky Mountain Research Station
Richard Birdsey, USDA Forest Service, Northeastern Research Station

Introduction

The increasing concentration of atmospheric carbon dioxide has raised concerns about the vulnerability of forests to potential changes in climate and climate variability. These concerns have prompted governments around the world to commission technical assessments on the impact of climate change on the environment and the economy. Based on the current scientific information within these assessments, governments have initiated negotiations on policy actions to reduce greenhouse gas emissions and to address the vulnerabilities of the ecological, economic, and social systems to climate change. Critical to policy formulation is a periodic synthesis of the ever-expanding knowledge on forest ecology, the impact of climate on forests and of forests on climate, forest management, the socio-economic value of trees and forests, and the role of forests in the global carbon cycle.

The Forest Service conducts periodic assessments of the condition of forest and rangeland resources under the authority of the Renewable Resources Planning Act (RPA). The structure of these periodic assessments allows for the synthesis and integration of the current state of scientific knowledge (U.S. Department of Agriculture Forest Service 1989, 1994). As part of the RPA process, this report is a synthesis of current information that assesses the impact of climate change on U.S. forests. Policy questions critical to understanding the impact of global climate change on current and future trends (Joyce et al. 1997) form the basis for the subsequent chapters in this report. This chapter describes the synthesis of scientific information and assessment of the impacts of climate on forests, current understanding of the global climate, and the policy questions addressed in this assessment.

The Synthesis of Scientific Information

International Syntheses

Mandates to synthesize scientific information for policy formulation have developed from international organizations, international agreements between countries, and laws within countries (fig. 1.1). Internationally, countries have worked together to organize the scientific community to study the impact of climate change on the climate system, global ecosystems, and social and economic systems. Within the United States, a series of laws have mandated these assessments, which in turn have supplied information to international efforts. To provide context, we introduce this chapter by describing the development of international and U.S. assessments on climate change.

The United Nations Environmental Programme and the World Meteorological Organization established the Intergovernmental Panel on Climate Change (IPCC) in 1988 in order to: 1) assess available scientific information on climate change; 2) assess the environmental and socio-economic impacts of climate change; and 3) formulate response strategies. The first assessment reports were completed in 1990 (Houghton et al. 1990; IPCC 1991), the second reports were completed in 1995 (Bruce et al. 1996; Houghton et al. 1996; Watson et al. 1996), and the third report is being written. These recent IPCC assessments have identified the importance of integrating the ecological and the economic and social analyses (Houghton et al. 1996; Bruce et al. 1996) to develop policy direction for mitigation and adaptation to an increasingly changing climate. The third assessment will rely on country assessments such as the U.S. assessments where the analysis can focus more closely on the impact of climate change on individual countries.

In 1992, the United States and over 50 other nations signed the Framework Convention on Climate Change (FCCC), an international agreement with no binding obligations. The policy objective identified in the FCCC was to achieve "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." In addition, these countries agreed that "such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." The signing of this agreement initiated a series of international meetings, so-called Conference of the Parties (COP), at which negotiators determine the mechanisms by which greenhouse gas concentrations could be stabilized globally (fig. 1.1).

After signing the FCCC, the United States developed policy and preferred actions to stabilize U.S. emissions by the year 2000 at the 1990 levels (Clinton and Gore 1993; U.S. Dept. of Energy 1994). Strategies within the Climate Change Action Plan included emission-reducing activities within the transportation and manufacturing sectors of the economy, and carbon storage activities in the forest

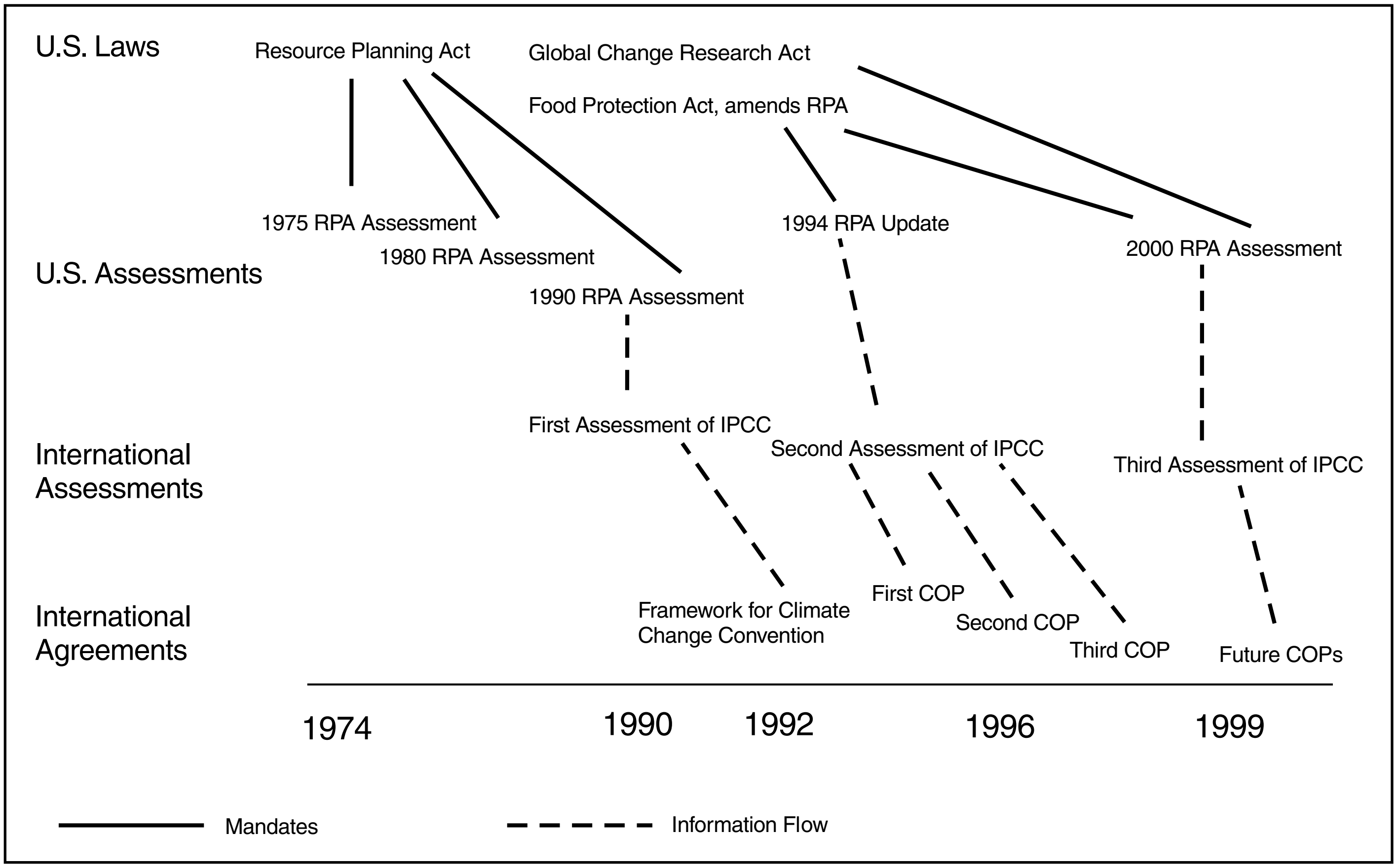

Figure 1.1—Laws and International Agreements mandating climate change assessments in the United States and internationally.

sector. The forest sector currently sequesters more carbon than it emits, and there are opportunities to increase this offset of fossil fuel emissions in the near-term. The proposed activities included accelerating tree planting and encouraging forest management evaluation in nonindustrial private forests. These carbon-storage activities would allow time to develop ways to reduce fossil fuel emissions.

A discussion on the importance of greenhouse gas stabilization led countries at the Third Conference of the Parties, held in Kyoto, Japan, in December 1997, to produce an agreement that included binding targets for reducing emissions and flexible implementation where targets would vary by country and groups of countries. Under the terms of the agreement, which has not yet been ratified by the U.S. Senate, the U.S. is bound to reduce emissions 7% below 1990 levels by 2008-2012. This reduction by 2012 is substantial, given that increases in population and economic expansion would increase future emissions in the absence of controls. Only reduction activities initiated in 1990 or later may be counted, since this is the reference point against which all future changes will be measured. These discussions included the role of forestry and land use change in stabilizing and mitigating carbon emissions. Negotiators considered the potentially important role of forest management in the ability of the United States to meet its binding targets of greenhouse gas emissions; yet, it is still not clear whether forest management will be included.

The importance of forests in maintaining the global carbon cycle was recognized formally for temperate and boreal forests in the Santiago Declaration, a statement signed in 1995 by the governments of Australia, Canada, Chile, China, Japan, the Republic of Korea, Mexico, New Zealand, the Russian Federation, and the United States. This statement identifies a comprehensive set of criteria and indicators for forest conservation and sustainable management for use by government policy makers. A criterion is a category of conditions or processes by which sustainable forest management may be assessed, and it is characterized by a set of related indicators that are monitored periodically to assess change. The United States is implementing many of these criteria and indicators within forest inventory and monitoring programs nationally. Criterion 5 is the maintenance of forest contribution to global carbon cycles.

U.S. Laws and the Forest Service Resource Assessments

The Forest and Rangeland Renewable Resources Planning Act of 1974 directed the Secretary of Agriculture to prepare a Renewable Resources Assessment in 1975 and a decadal update starting in 1979. The assessment was to include "an analysis of present and anticipated uses, demand for, and supply of the renewable resources, with consideration of the international resource situation, and an emphasis of pertinent supply, demand and price relationships trends." Since 1974, there have been 3 national assessments and two updates which have reviewed the current and likely future condition of forest and range resources including wildlife, water, timber, recreation, range forage, and minerals. Assessments typically include: 1) description of the current status of the resource; 2) a projection of supply of and demand for resource outputs; 3) social, economic, and environmental implications of the projections; 4) management opportunities to improve the resource situation; and 5) a description of Forest Service programs and responsibilities. The results of the RPA assessment are used as the factual basis for formulating future renewable resource management programs. The structure of these on-going assessments provides a mechanism by which current scientific information can also be synthesized periodically to address policy questions.

Subsequent laws within the United States mandated assessments of the impact of climate change on the U.S. environment and economy (fig. 1.1). The Global Change Research Act of 1990 requires the National Science and Technology Council to: 1) assess current human-induced and natural trends in global change; 2) analyze effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and 3) project major trends for the subsequent 25 to 100 years. The 1990 Food Protection Act amends the 1974 Resources Planning Act and requires the Forest Service to: 1) assess the impact of climate change on the condition of renewable resources on forests and rangelands, and 2) identify the rural and urban forestry opportunities to mitigate the buildup of atmospheric carbon dioxide.

Since the Amendment of the RPA, the RPA assessments have included an analysis on the vulnerability of U.S. ecosystems to changes in climate, and the potential impact on the social and economic systems from changes in climate. The 1989 assessment included a review of the current scientific understanding of the potential effects of global climate change on forests (Joyce et al. 1990). The next assessment update in 1993 used an integrated modeling framework to analyze the impact of climate change on ecosystem productivity, timber supply and demand, and carbon storage (Joyce 1995; Joyce et al. 1995). We use this modeling framework to structure our current synthesis of the impact of climate change on U.S. forests (fig. 1.2). The following chapters review our ability to quantify the impacts of a changing climate on changes in vegetation communities (Chapter 2), forest productivity (Chapter 3), forest economy, land area, timber inventory (Chapters 4 and 5), and carbon stored in forests, in wood products, and in landfills and dumps (Chapters 5, 6, 7 and 8).

Six policy questions related to the impact of global climate change on forests (Joyce et al. 1997) form the basis for the subsequent chapters in this report. This chapter describes mandates and structures of synthesizing scientific information and assessing the impacts of climate on the forest sector, current understandings of the global climate, and policy questions addressed in this assessment.

Understanding the Dynamics of Climate

Climate Dynamics, Greenhouse Gases, and Global Carbon Cycle

Identifying the vulnerabilities of ecosystems and economies to climate variability and change depends on an understanding of the sensitivity of those systems to climate. Analyzing the effectiveness of policy instruments in stabilizing greenhouse gases, such as sequestering carbon in forests, depends on an understanding of several factors: climate processes, the physical changes in climate arising from all greenhouse gases and aerosols, biospheric and oceanic interactions, and the influence of humans on climate processes and forest biogeochemistry through activities such as forest management and land use change. We briefly review current observations on changes in atmospheric chemistry, changes in global and U.S. climates, and the influence of humans on the earth's climate system.

Certain atmospheric gases have the potential to warm the atmosphere and are collectively known as greenhouse gases: carbon dioxide, methane, nitrous oxides, chlorofluorocarbons, and water vapor (Houghton et al. 1996). The amount of warming is a function of the ability of these gases to absorb solar radiation (radiative properties of the gases) and the atmospheric concentration of each gas. The radiative property of a gas is constant, but the atmospheric concentrations of these gases are altered by natural processes and human activities. It is the rise in atmospheric concentration of these gases that is of concern globally.

The atmospheric concentration of carbon dioxide, methane, nitrous oxides, and the chlorofluorocarbons has

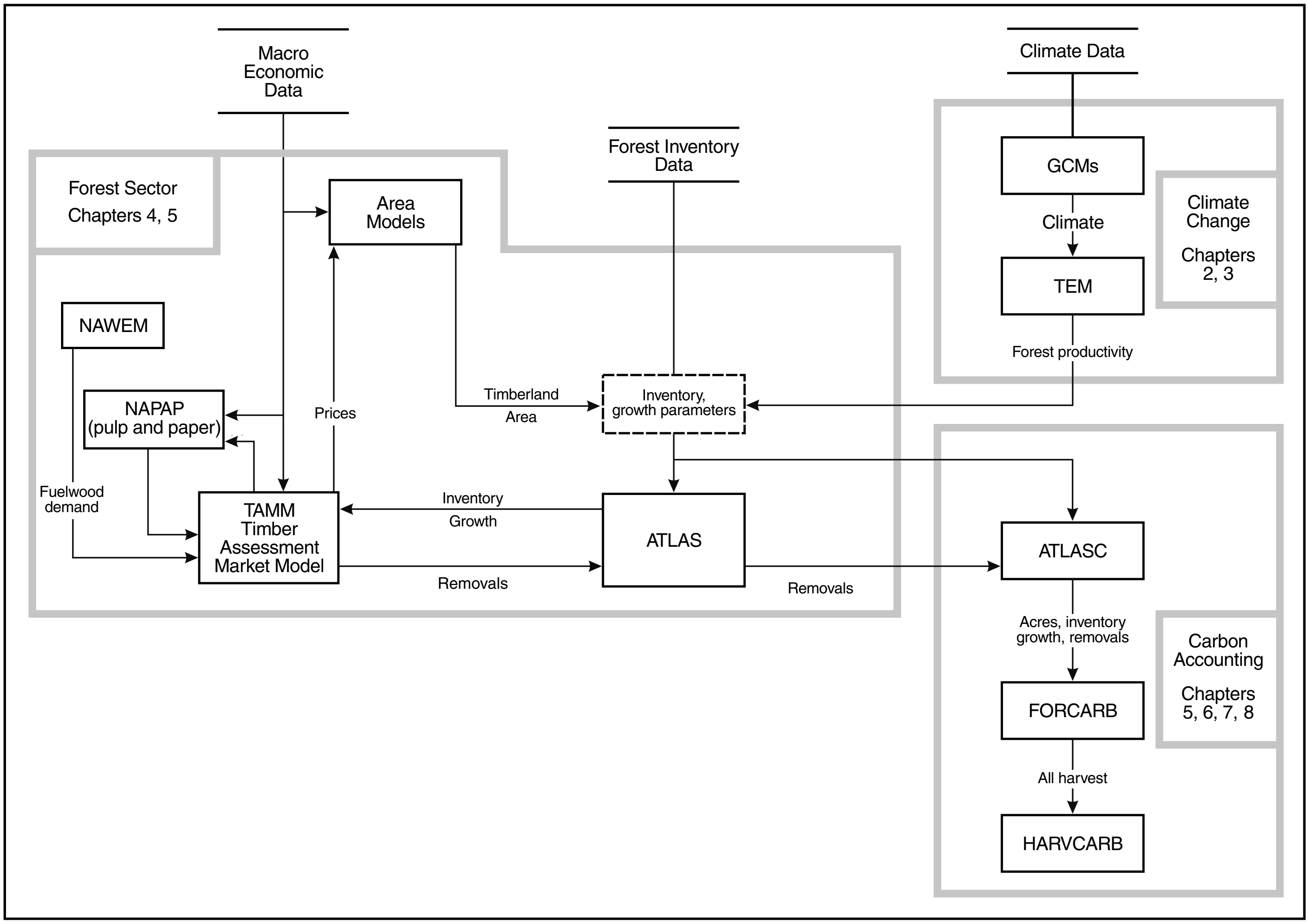

Figure 1.2—Components of the Integrated Modeling system used in the 1993 Forest Service RPA Assessment Update.

increased since pre-industrial times (table 1.1). Increases range from 13 percent for nitrous oxides to 145 percent for methane. Moreover, the atmosphere did not contain chlorofluorocarbons in pre-industrial times. Increases in carbon dioxide are mainly the result of fossil fuel emissions from industrial and domestic activities and land use conversions. Methane increases result from the production and use of fossil fuel and from anthropogenic activities such as rice cultivation and livestock production. The sources of nitrous oxides are small and hard to quantify, but include agriculture and industrial processes. The rates of concentration changes (table 1.1) are positive except for CFC-11, which is being controlled as a result of the Montreal Protocol. The positive rates of change demonstrate that atmospheric concentrations will continue to increase for these greenhouse gases, unless the activities influencing these concentrations are modified.

While concentrations of greenhouse gases are sources of atmospheric warming, other processes have recently been identified that also influence the earth's energy. Aerosols, tiny particles of liquid or solid matter suspended in the atmosphere, can be derived from many different materials including sea salt, soil, smoke, and sulfuric acid (Schimel et al. 1996). They increase the scatter of incoming solar radiation, sending some radiation away from earth. They are also a part of the cloud-forming process. In both of these ways, aerosols can influence the earth's temperature. The length of time that aerosols remain in the atmosphere is much less (a few weeks) than the residence time of carbon dioxide (approximately 100 years). In addition, human-produced aerosols do not mix throughout the globe like carbon dioxide (Charlson et al. 1992). They tend to remain near the area of generation and thereby have an impact on the regional climate.

Land management activities influence the uptake and release of greenhouse gases. The processes that influence these carbon fluxes operate at different spatial scales and time frames. Currently, the main sources of carbon dioxide include fossil fuel consumption and land use change, particularly deforestation in the tropics. The main res-

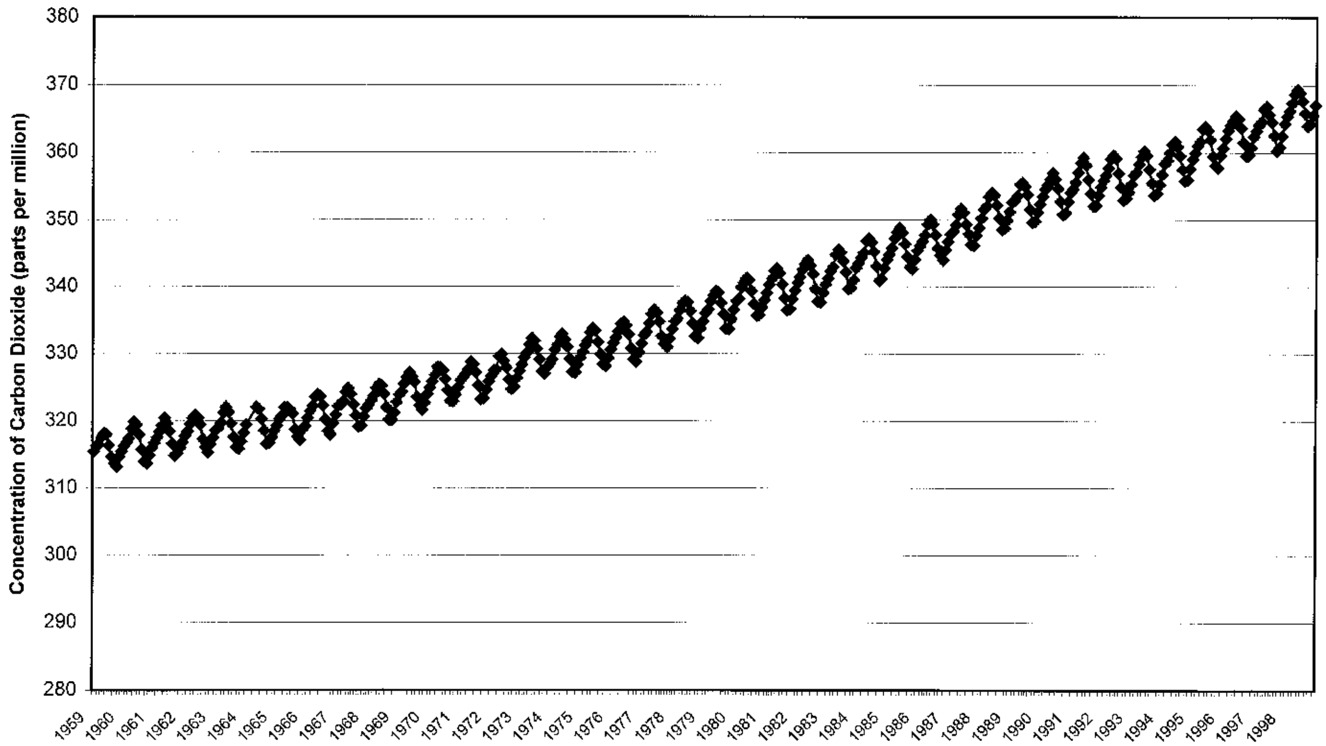

Figure 1.3—Observed concentration of atmospheric carbon dioxide in parts per million at Mauna Loa, Hawaii, from 1959 to 1998. (Source: C. D. Keeling, Scripps Institution of Oceanography)

Table 1.1—A sample of greenhouse gases affected by human activities (Houghton et al. 1996).

	CO_2	CH_4	N_2O	CRC-11	HCFC-22 (A CFC substitute)	CH_4 (A perfluorocarbon)
Pre-industrial concentration	~280 ppmv	~700 ppbv	~275 ppbv	zero	zero	zero
Concentration in 1994	358 ppmv	1720 ppbv	312[1] ppbv	268[1] pptv[2]	110 pptv	72[1] pptv
Rate of concentration change[3]	1.5 ppmv/yr	10 ppbv/yr	0.8 ppbv/yr	0 pptv/yr	5 pptv/yr	1.2 pptv/yr
	0.4%/yr	0.6%/yr	0.25%/yr	0%/yr	5%/yr	2%/yr
Atmospheric lifetime (years)	50–200[4]	12[5]	120	50	12	50,000

[1] Estimated from 1992–93 data.
[2] 1 pptv = 1 part per trillion (million million) by volume.
[3] The growth rates of CO_2, CH_4, and N_2O are averaged over the decade beginning 1984; halocarbon growth rates are based on recent years (1990s).
[4] No single lifetime for CO_2 can be defined because of the different rates of uptake by different sink processes.
[5] This has been defined as an adjustment time which takes into account the indirect effect of methane on its own lifetime.

ervoirs for carbon storage include the atmosphere, the ocean, and the vegetation. Incorporation of carbon into vegetation is the fastest process, and atmospheric concentrations throughout the year reflect the seasonal growth of vegetation (fig. 1.3). Transfers to soils and ocean depths operate on the decade-to-century time-scale.

Transfers of carbon dioxide between the atmosphere, ocean, and land at the global scale have been examined using a budgeting approach (Houghton et al. 1996). The amount of carbon dioxide that remains in the atmosphere is used to project likely future changes in the global climate. Emissions from fossil fuel combustion and cement production are the larger share of the carbon sources identified (table 1.2). Atmospheric sampling and forest inventories indicate that the carbon source of land clearing in the tropics is approximately balanced by the carbon reservoir of forest regrowth in the Northern Hemisphere. Experimental research suggests that the uptake of carbon in vegetation may be stimulated by increased atmospheric carbon dioxide and nitrogen fertilization from the deposition of nitrogen in the atmosphere (Kauppi et al. 1992, Aber et al. 1998, Magill et al. 1997). The future role of vegetation in the global budget is highly uncertain because of our lack of understanding about processes such as fertilization from atmospheric carbon dioxide and our inability to predict future rates of deforestation in the tropics and regrowth in the mid-latitudes (Houghton et al. 1996, Watson et al. 2000). Understanding the uptake and release of carbon in forested ecosystems, especially as affected by management activities, will be important in addressing the role of forestry, not only in mitigating greenhouse gas emissions, but also in the processes influencing the global carbon budget (Schimel et al. 2000).

Analyses in the recent RPA Update focused on the role of forestry in releasing carbon through harvest and in storing carbon through growth and land conversion to forests on the U.S. mainland. The net effect of these activities in the United States comprise an estimated carbon sink of approximately 0.3 GtC/yr (Birdsey and Heath 1995), a substantial portion of the total uptake by the Northern Hemisphere. These analyses are set in the context of the global budget of carbon in order to determine what role U.S. forests might play in mitigating carbon emissions and thereby to help stabilize the concentrations of carbon dioxide in the atmosphere.

Table 1.2—Annual average anthropogenic carbon budget for 1980 to 1989. CO_2 sources, sinks, and storage in the atmosphere are expressed in GtC/yr (where GtC is gigatons of carbon) (Houghton et al. 1996).

CO_2 sources	
(1) Emissions from fossil fuel combustion and cement production	5.5 ± 0.5[1]
(2) Net emissions from changes in tropical land-use	1.6 ± 1.0[2]
(3) Total anthropogenic emissions = (1) + (2)	7.1 ± 1.1
Partitioning amongst reservoirs	
(4) Storage in the atmosphere	3.3 ± 0.2
(5) Ocean uptake	2.0 ± 0.8
(6) Uptake by Northern Hemisphere forest regrowth	0.5 ± 0.5[3]
(7) Inferred sink: 3-(4+5+6)	1.3 ± 1.5[4]

[1] For comparison, emissions in 1994 were 6.1 GtC/yr.

[2] Consistent with Chapter 24 of IPCC Working Group II (Watson et al. 1996).

[3] This number is consistent with the independent estimate, given in IPCC Working Group II (Watson et al. 1996), of 0.7 ± 0.2 GtC/yr for the mid-land high latitude forest sink.

[4] This inferred sink is consistent with independent estimates, given in Chapter 9 of IPCC Working Group I (Houghton et al. 1996), of carbon uptake due to nitrogen fertilization (0.5 ± 1.0 GtC/yr), plus the range of other uptakes (0-2 GtC/yr) due to CO_2 fertilization and climatic effects.

Observed Trends in Climate at the Global Scale

At the global scale, increases in air temperature and in precipitation have been documented in the historical record of observation (Houghton et al. 1996). Both sea surface and land surface temperatures indicate a warming pattern. While observed changes related to temperature generally have a higher confidence than observed changes in the hydrological cycle, precipitation has also increased 1% globally.

Since the late 19th century, near-surface air temperatures have risen from 0.3 to 0.6°C, paralleling similar increases seen in near-surface ocean temperatures. The most reliable period of observation, the last 40 years, indicates a warming of 0.2 to 0.3°C for the global average surface temperature (Houghton et al. 1996). While temperatures have increased over time in urban centers, the increases in urban temperatures and the expansion of urban areas contributes minimally to global surface warming (Easterling et al. 1997). Urbanization may be important in some regions, however. Similarly, desertification has influenced local climates, but has a negligible effect on global temperature changes (Houghton et al. 1996).

The difference between the surface maximum and minimum daily temperatures has decreased since the middle of the 20th century based on an analysis of over 54 percent of the global land area (Easterling et al. 1997). This narrowing of the daily maximum and minimum temperatures is the result of warmer nighttime temperatures, which may reflect not only the increase of carbon dioxide but also increased cloud cover. Daytime clouds obstruct the daytime sunshine, while nighttime clouds reduce the amount of terrestrial radiation escaping at night.

A number of indirect indicators support these observed increases in temperature globally. The 20th century retreat of mountain glaciers and the underground temperatures in boreholes are seen as indirect indicators supporting these warming estimates. Houghton et al. (1996) reported mass balance declines for the six glaciers for which long observational data are available. South Cascade in Alaska showed the largest loss in mass balance. Underground temperatures in boreholes have been observed to warm in New England, Canada, Alaska, France, and the ice sheet in the Arctic regions, but other areas have shown no changes. An analysis of all the North American studies concluded that underground temperatures warmed between 0.3 and 4.0 ^{0}C since the 19th century (Deming 1995). The increasing trends in precipitation have also been corroborated regionally with indirect indicators such as streamflow, lake levels, and where available, soil moisture.

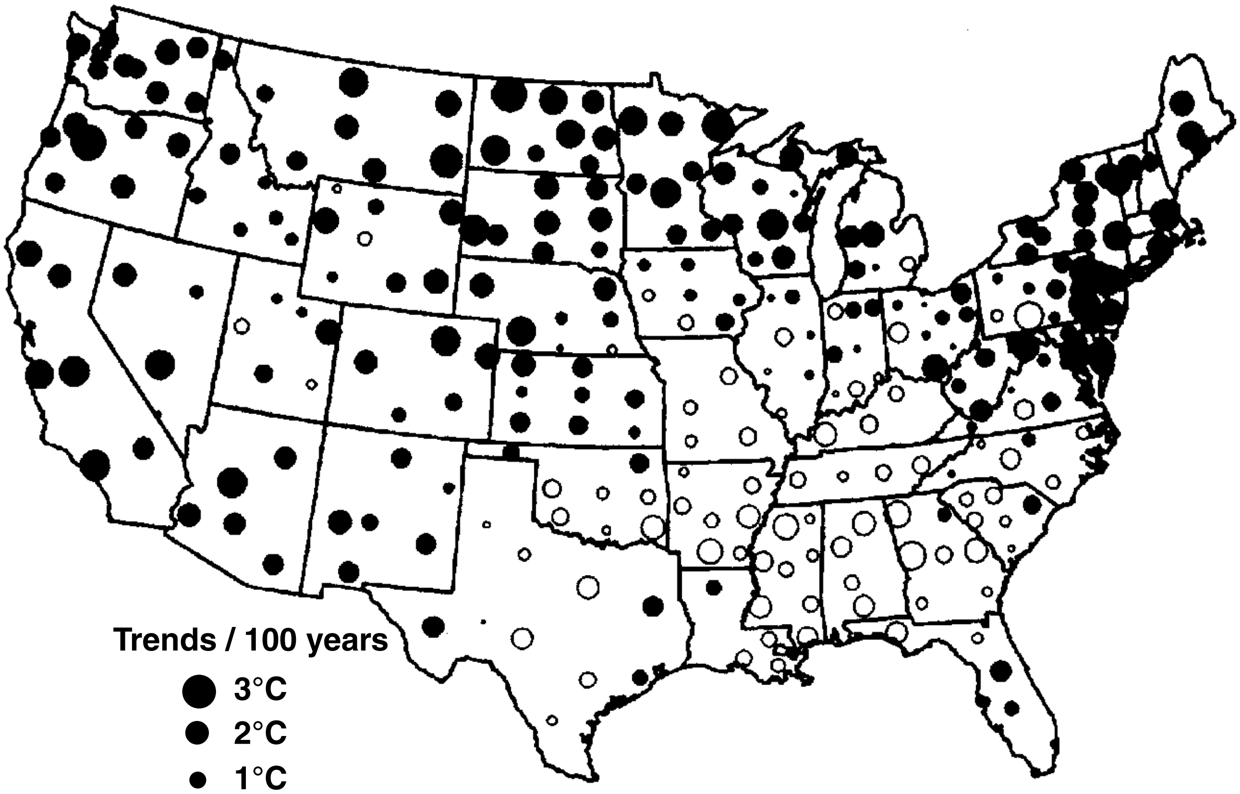

Figure 1.4—Temperature trends (1900-94 converted to mean temperature in °C per 100 years) centered within state climatic divisions are reflected by the diameter of the circle centered within each climatic division. Solid circles represent increases and open circles, decreases (from Karl et al. 1996).

The variability of climate is calculated from the historical records. Globally, the data are inadequate to assess whether climate variability has changed in response to elevated greenhouse gases (Houghton et al. 1996). No global-scale patterns in drought frequency or intensity or variation in rainfall events or extremes has emerged from the analysis of the available data. Sufficient data have been available to examine these trends for some regions, such as described below for the United States.

Indicators of Change in the U.S. Climate

An analysis of the near-surface air temperature reveals that temperatures have warmed over much of the United States in the last 100 years (fig. 1.4) (Karl et al. 1996). Temperature trends at the national scale, if represented with a linear trend, indicate a rise of about 0.4°C over 100 years. This rise occurs mainly in the first six months of the year. Regional records show the South with a slight cooling (1°C/100 years) and the northeast, northcentral, and western parts of the United States with a warming trend of 1 to 2°C. At the continental scale, Watson et al. (1998) reported the highest increases in warming occurred along an area extending from northwestern Canada across the southern Canada/northern U.S. region to southeastern Canada and the northeastern United States. The temporal pattern of these increases indicates an increase in warming from the 1920s to the 1940s and again from the 1970s to the 1990s.

Within the United States, precipitation was shown to have increased since 1970 about 5%, mainly the result of increases in precipitation in the last six months of the year, and primarily in autumn (Karl et al. 1996). The largest increases, up to 20%, were seen in the Gulf Coast states, the lower northeastern part of the United States, and the midwestern states (fig. 1.5). However, states such as California, Montana, Wyoming, North Dakota, parts of Colorado, and Nebraska have actually had a decrease in annual precipitation of similar magnitude.

Karl et al. (1996) present a framework for examining potential changes in the U.S. climate. They developed two indices that reflect the behavior of individual climate metrics that would likely reflect changes in the climate as a result of increasing concentrations of greenhouse gases. Their Climate Extremes Index supports the notion that the climate of the United States has become more extreme in recent decades. Their U.S. Greenhouse Climate

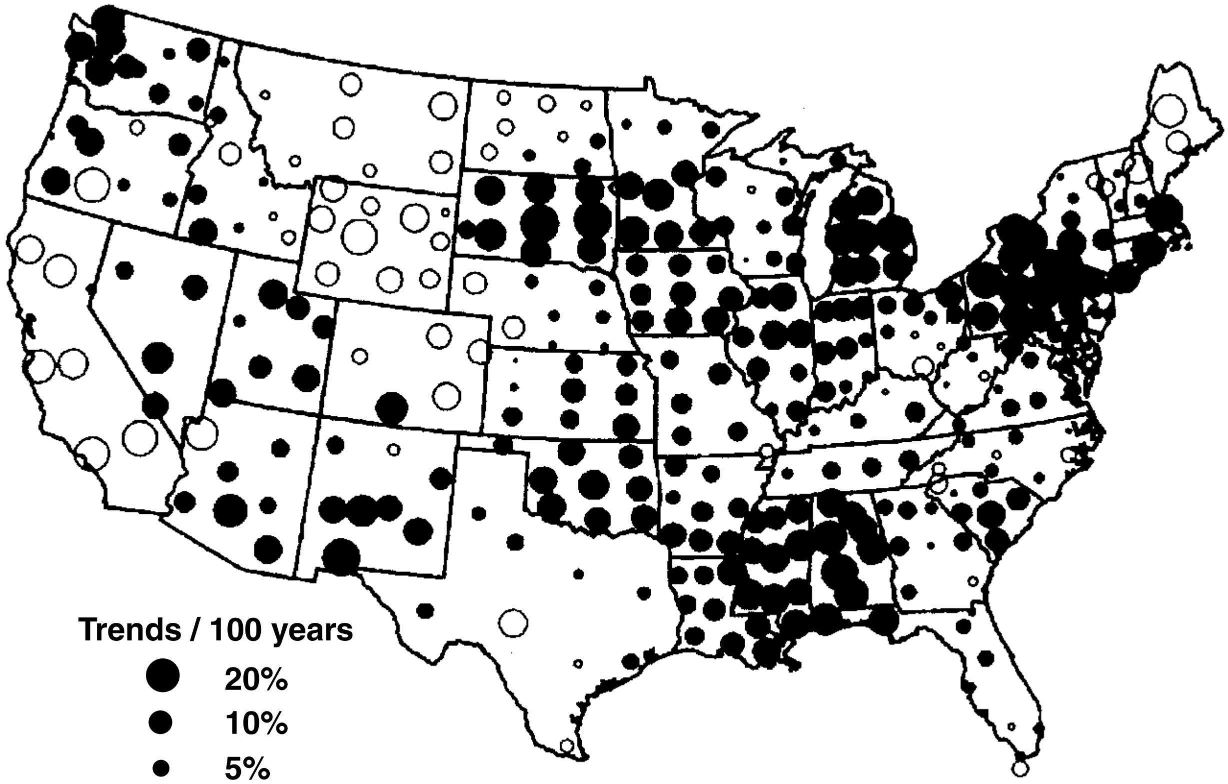

Figure 1.5—Precipitation trends (1900-94 converted to percent per century) centered within state climatic divisions are reflected by the diameter of the circle centered within each climatic division. Solid circles represent increases and open circles, decreases (from Karl et al. 1996).

Response Index is consistent with an enhanced greenhouse effect. However, neither response is large enough to conclude that the increase in extremes reflects a nonstationary climate, or that the increase in the Greenhouse Climate Response Index may be the result of other factors including natural climate variability.

The increase in extremes is influenced markedly by three precipitation indicators: the frequency of long-term drought severity and moisture excess; the frequency of extreme 1-day precipitation events; and a much greater than normal number of days with precipitation. When Karl et al. (1996) analyzed the extremes associated with drought severity and moisture excess, they determined that there was considerable decadal variability in drought severity and in moisture surplus. The likelihood that these occurrences arose from a quasi-stationary climate was 25%. In the last several decades, however, they noted a tendency for more of the area in the United States to be either in a drought or to have severe excess moisture. Karl et al. (1996) determined that the proportion of the country that has had a much greater than normal amount of precipitation derived from extremely heavy (greater than 50.8 mm or 2 in) 1-day precipitation events could be reliably computed from climate data available since 1910 (fig. 1.6). They concluded that the steady increase in area of the United States affected by extreme precipitation events would be highly unlikely (less than 1 chance in 1000) in a quasi-stationary climate. The percentage of the conterminous U.S. area with the number of wet days much above normal also increased beyond what one would expect for a stationary climate. This increase in the number of wet days parallels the increase in precipitation at the national scale. The proportion of area in the United States with a much greater than normal number of dry days did not change over the century (Karl et al. 1996).

An increase, but of more recent nature, was seen in the percentage of the conterminous U.S. area with a much above normal cold season (October through April) precipitation (fig. 1.7). Here the increase is most noticeable since 1970. Another indicator of potential shifts was the decrease in area affected by much below normal maximum temperatures (not shown here).

Recent work has synthesized many climate metrics, including biologically meaningful indicators, to show a rapidly warming climate in Alaska. Chapman and Walsh (1993) documented a significant warming trend in the temperature records over the last few decades for most of Alaska, with winter temperatures warming more than

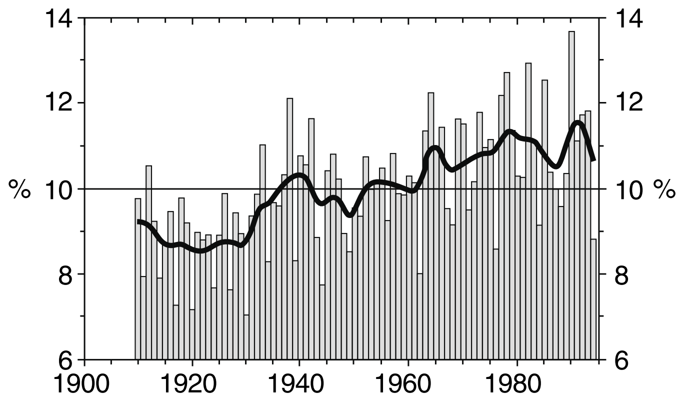

Figure 1.6—Percentage of the conterminous U.S. area with a much above normal proportion of total annual precipitation from 1-day extreme (more than 2 inches) events (from Karl et al. 1996).

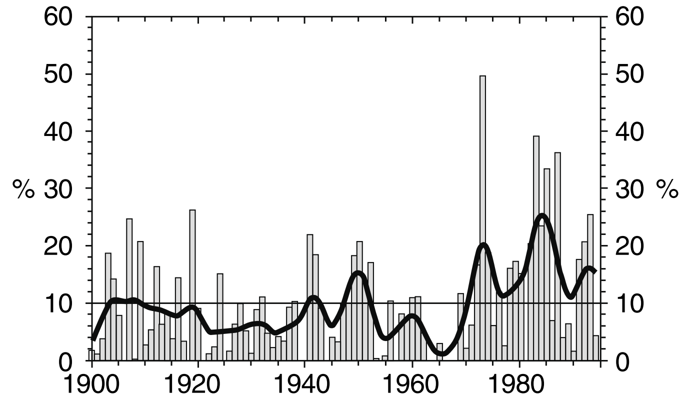

Figure 1.7—Percentage of the conterminous U.S. area with much above normal cold season (October through April) precipitation (from Karl et al. 1996).

summer temperatures. Jacoby et al. (1995) confirmed this recent trend by analyzing tree rings. They also concluded that temperatures are near the highest level of the past 3 centuries, an observation also made by Lachenbruch et al. (1988) from data derived from arctic boreholes. Most recently, Myneni et al. (1997) examined atmospheric CO_2 trends and changes in the normalized difference vegetation index (NDVI - an index of greenness). They concluded that the active growing season lengthened by about 12 days and that winter temperature increased by 4°C between 1981 and 1991 at latitudes above 45°N. Before this recent climate research, Oechel et al. (1993) reported changes in the carbon dioxide flux from Arctic tundra ecosystems, shifting the carbon balance from a net carbon dioxide sink to a source of carbon. This increase was presumed to be the result of increasing soil temperatures, soil aeration, and depth of soil thaw (Oechel et al. 1993).

Predicting Future Climates and the Vegetation Response

Atmospheric-Biospheric Relationships

Forests and climate are intimately connected in the United States. The North American climate is influenced by the region's size, topography, and the widely varying temperatures of the surrounding oceans. The current distribution of forests is strongly tied to these climate patterns.

In the Pacific Northwest of the United States, local climates are influenced by elevation, proximity to the Pacific Ocean, prevailing winds, and the north-south-oriented mountain ranges. Similarly, local climates on the eastern coast are influenced by proximity to the ocean and the Gulf of Mexico, and the episodic extreme events such as hurricanes. Even climates in the interior of the United States are influenced by large bodies of water such as the Northcentral communities surrounding the Great Lakes and the communities on the eastern side of the Great Salt Lake in Utah. For a large part of the North American continent, disturbances in the upper-level westerly winds play an important role in the temperature and moisture regimes. The Polar Front refers to the surface boundary between the colder, drier Arctic air and the warmer, moister air in the south. Disturbances in the upper level westerly winds shift the position of the upper level jet stream, and hence the Polar Front, back and forth across the North American continent. In the colder months of the year, this front moves slowly back and forth across the United States, bringing colder Arctic air to the northern and parts of the southern United States. Spring and fall see shorter, weaker systems moving quickly across the continent. In the summer the Polar Front retreats far into northern Canada. Because of these climate influences, the current temperature and precipitation gradients in the eastern half of the United States are strong in both the north to south and east to west directions.

Forests dominate the East and parts of the West. Major timber producing regions include the moist Pacific Northwest coast, the warm and moist Southeast, and the moist but cooler Northcentral region. Annual precipitation is highest along the Pacific Northwest coast and in the Southeast, centered mainly along the Gulf Coast states (Watson et al. 1998). High precipitation rates, low evaporative demands, and moderate temperatures characterize the Pacific Northwest climate (Lassoie et al. 1985). The forests in the East respond to climates influenced by proximity to the ocean and shifts in the continental air masses (Hick and Chabot 1985). Forests on the east coast periodically experience major tropical storms and hurricanes.

Any change in climate and climate variability has the potential to alter the structure, function, and geographic distribution of forests.

In the 1993 RPA Update, climate scenarios from four General Circulation Models (GCM) were used to examine the impact of climate change on forest productivity (Joyce et al. 1995). These global models provided equilibrium climates under elevated atmospheric carbon dioxide concentrations at a coarse spatial resolution. We review below the improved understanding of climate dynamics since this analysis. Another area where the understanding of climate dynamics has improved but there remains much uncertainty is the interaction between the land use and atmospheric dynamics. We also review below recent research identifying the contributions that land use makes to local climate conditions.

Improvements in Climate Scenarios

Since the development of these early GCMs, improvements have resulted in better depiction of large scale features of the climate system such as the seasonal, geographical, and vertical variations in climate (Houghton et al. 1996). Our ability to detect climate change is closely linked with our ability to predict the temporal and spatial variability of climate. Within the GCMs, the variability in results is broadly comparable to the observed variability in time and space (Houghton et al. 1996). Improved GCMs capture the relatively smaller variability over the oceans and the larger variability over continental interiors. However, only recently has the interannual variability associated with the El Nino-Southern Oscillation phenomenon been captured by a coupled atmospheric and ocean model, the Hadley GCM (Tett et al. 1997). The Hadley model and several other GCM models represent a significant improvement in the projection of climate change through the three-dimensional representation and interaction of atmospheric processes, oceanic processes, and the land surface properties on a time-dependent basis (Houghton et al. 1996). These scenarios are referred to as transient scenarios, in contrast to the earlier equilibrium scenarios. These computationally intensive simulations allow an examination of the behavior of climate as human-induced emissions increase over time.

While climate scenarios in the Second IPCC Assessment included the nature of change over time (Houghton et al. 1996), the IPCC analysis of the impact of climate change on ecosystems, including forests, was based on the earlier equilibrium climate scenarios. Only now is research being reported that has used the transient scenarios to examine the impact of climate change on forests (Neilson 1998). However, the land surface properties of these improved atmospheric-ocean coupled models is static; that is, the land surface properties, such as vegetation, do not change over time in response to climate changes or human activities. Recent work has shown the impact of land surface properties on climate modeling (Pitman et al. 1999). The development of feedbacks between land surface properties and the atmosphere-ocean processes is another area of needed research.

The addition of aerosols to the GCMs has resulted in closer agreement between model simulations and the observed global mean surface temperature. The release of stratospheric aerosols from the 1991 Mount Pinatubo eruption was used to exercise a climate model; the model results of a shift in the global temperature variation agreed closely with the observations. Analyses with the Hadley GCM indicate that the influence of aerosols varies by season and region of the globe (Mitchell and Johns 1997). In the winter, aerosols cool the warming influence of carbon dioxide; in the summer, the influence of carbon dioxide on the hydrological cycle is disrupted. Regional climates in Europe and Southeast Asia are significantly impacted by the inclusion of aerosols in the model.

These improvements in GCMs have been outpaced by an equally important increase in our understanding of the complexity of the climate system and the identification of additional processes that need to be included in the climate models. The range of temperature increases (1.5°C to 4.5°C) given in Houghton et al. (1990) and Houghton et al. (1996) in response to a doubling of carbon dioxide concentration results from model uncertainty associated with internal feedbacks such as water vapor feedback, cloud/radiative feedback, ice and snow albedo feedback, and uncertainties in the representation of ocean circulation and land-surface/atmosphere interactions.

Clouds influence the global temperature both as a cooling agent and as a warming agent. The formation of clouds is dependent upon the interactions of atmospheric water and aerosols. The uncertainty of the temperature rise is primarily the result of our lack of understanding of cloud processes. Sea ice coverage varies between GCMs and further refinement of this aspect will increase their accuracy (Houghton et al. 1996). Changes in the climate from anthropogenic emissions will influence environmental factors such as soil moisture, albedo, and vegetation. Changes in these surface properties will, in turn, affect the local climate.

GCMs typically operate at a coarse resolution. The complex topography of landscapes such as the western United States is not represented in detail in these GCMs. At regional scales, the interactions between the atmosphere and the surface (topography, vegetation) are important. The regional influence of human-generated aerosols will likely be significant as these aerosols do not disperse widely from their sources of generation. Further, most GCMs do not include changes in land use and these have been shown to have significant impact on temperature and precipitation changes, especially in the tropics and subtropics (Houghton et al. 1996).

Watson et al. (1998) concluded that limited confidence can be placed in regional climate projections because these projections are unable to capture present-day climates, and inter-model variability is quite large. Although statistical downscaling techniques and nested regional models have been used to refine regional climate projections, the current GCMs do not capture the complex topographical features, large lake systems, and narrow land masses that significantly affect regional and local change scenarios (Houghton et al. 1996). This degree of uncertainty complicates the assessment of the impact of climate and climate variability on forest resources at the local scale. Houghton et al. (1996) identified the following urgent scientific problems requiring attention: improved understanding of regional patterns of climate change including land-surface processes and their link to atmospheric processes; coupling of scale between global climate models and regional and smaller scale models; and simulations with higher resolution climate models.

Influence of Human-Induced Land Use Change on Climate

Land use change influences atmospheric-biospheric relationships (Cotton and Pielke 1995; Houghton et al. 1996) through changes in atmospheric chemistry and the surface characteristics such as albedo. The conversion of vegetation from forest to grassland, through harvest or burning, changes the roughness and albedo of the land surface, influencing the climate. Biomass burning is used to clear land for shifting cultivation, to convert land from forest to agriculture or grazing, to promote productivity of grasses or agricultural crops, and as an energy source (Crutzen and Andreae 1990). This burning produces trace gases and aerosol particles that influence atmospheric chemistry and climate. When tropical forests were replaced by pasture within the Amazon basin, mean surface temperature increased about 2.5°C and annual evapotranspiration decreased by 30% (Nobre et al. 1991). Two other effects observed in the model simulations, larger diurnal fluctuations of surface temperature and vapor pressure deficit, have been observed in deforested areas in the Amazon (Nobre et al. 1991).

The schemes used in GCMs to depict the land surface, including vegetation, have increased in their complexity since the first IPCC assessment, but there is still considerable uncertainty in their ability to predict soil moisture, surface heat, and water fluxes in the absence of land use changes. The slow changes in reforestation and the dynamic impacts of land use changes such as deforestation are not incorporated into the current GCMs (Houghton et al. 1996).

Large-scale changes in vegetation cover have resulted from deforestation to agriculture and reforestation in New England (Foster et al. 1992) and fires and extractive uses in Colorado (Price 1991). These changes in vegetation and land use are often not climate related (Dale 1997) and are not included in GCM depictions of the earth's land surface. Even when climate scenarios are used to drive ecological or economic models, the climate-related changes in land cover and use projected in the ecological and economic models do not feed back to the climate models in most cases.

Some investigators have shown the impact of land use on regional climates. Pielke et al. (1997) used land use data to demonstrate the role that landscapes (particularly spatial heterogeneity) have on the development of weather disturbances, such as thunderstorms in the Great Plains. The urban heat island effect, where large masses of concrete absorb solar radiation, is well-documented. Bonan (1997) used a simulation model to examine the impact of the cumulative changes in land cover and land use in the United States on climate in the United States. Modern vegetation includes crops replacing grassland vegetation in the central U.S. and the needleleaf evergreen, broadleaf deciduous, and mixed forests of the eastern U.S. The modeling exercise indicated that temperatures were 1 degree C cooler in the eastern U.S. and 1 degree C warmer over the western U.S. in spring. Bonan (1997) reported that the sulfate aerosols in the atmosphere in the eastern U.S. offset the warming impact of the greenhouse gases locally there. A clearer understanding of how land use affects local climate will be important in managing landscapes under an altering climate.

Impact of Climate Change on Forests, Wood Products, and Carbon

Forest Service RPA and Global Change Research Program Assessment of Climate Change

To develop forest policy actions to meet the challenges and opportunities of climate change, an integrated assessment is needed where climate information, forest productivity, forest management, the demand for forest products, and carbon sequestration is considered holistically. As described in Watson et al. (1998), current approaches to integrated assessments fall into three main categories: 1) the "vertical" dimension, where integration occurs through the chain of effects from changes in atmospheric composition and climate to changes in biophysical systems to socioeconomic consequences; 2) the "horizontal" dimension, which emphasizes the interactions among systems, sectors, and activities; and 3) the "time" dimension, where trends in society are projected over the transient path of the projected climate. Each of these approaches offers important insight into questions surrounding the impact of climate and climate variability on the forest environment and economy. The most recent RPA climate change assessment was based on the vertical approach, with some consideration of the temporal dynamics (fig. 1.2). This report, in cooperation with the Forest Service Global Change Research Program, seeks to establish the foundation for the next quantitative analyses of the impact of climate change on forests.

The Forest Service Global Change Research Program (FSGCRP) was initiated in the late 1980s to provide the scientific basis to address three broad questions (Birdsey et al. 1997): 1) What processes in forest ecosystems are sensitive to physical and chemical changes in the atmosphere? 2) How will future physical and chemical climate change influence the structure, function, and productivity of forest and related ecosystems, and to what extent will forest ecosystems change in response to atmospheric changes? and 3) What are the implications for forest management and how must forest management activities be altered to sustain forest productivity, health, and diversity? Experimental studies, monitoring, and modeling research are an integral part of the FSGCRP. Through participation in the U.S. Department of Agriculture's Global Change Research Program, the FSGCRP is a part of the U.S. Government's Global Change Research Program (USGCRP). The USGCRP has been developed under the direction of the Executive Office of the President, through the National Science and Technology Council (NSTC) and its Committee on Environment and Natural Resources (CENR).

The FSGCRP and the RPA assessments have a common goal of assessing current and future resource trends. Questions critical to understanding the impact of global climate change on current and future trends are the focus of the joint FSGCRP-RPA assessment. Six policy questions were identified (Joyce et al. 1997) and these questions form the basis for the subsequent chapters in this report.

> What are the likely effects of increasing atmospheric carbon dioxide and prospective climate changes on ecosystem productivity, as measured by changes in net primary productivity?
>
> To what geographic extent will potential ecosystem types change or move across the United States, as measured in composition and boundary changes?
>
> What changes in forest productivity will occur as measured by changes in volume, growth, and biomass?
>
> What are the potential impacts on the forest sector under climate change, as measured by employment and timber prices?
>
> When forest policy questions for the RPA Assessment, such as reduced NFS harvest, are examined with and without climate change, do the forest sector impacts differ greatly in magnitude or kind?
>
> What are the opportunities and costs of emissions mitigation using forest ecosystem management and forest products technologies?

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