HLTH-3: Abiotic Factors

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How have abiotic factors including environmental stressors such as air pollution influenced the overall health of the South's forests and what are future effects likely to be?

1 Key Findings

- Sulfur deposition will continue to decrease and subsequently have less of a negative impact on forest ecosystem nutrient cycling, while future nitrogen deposition will be beneficial to most southern forests, which are nitrogen limited.
- High-elevation spruce-fir forests in the Southern Appalachian Mountains are the only forests for which significant damage is linked to acid deposition.
- The overall health of hardwoods, oak-pine, and southern pine forests has not been shown to be adversely affected by acid deposition.
- Regionally, there is no evidence that acid precipitation is causing significant damage to stream chemistry in the Southern United States. Water quality in some streams in the Southern Appalachian Mountains is decreasing.
- Ozone-related annual growth reductions for pine seedlings across the South are probably between 2 and 5 percent. Tree water stress or forest drought is thought to protect seedlings from the negative effects of ozone. Any protective benefits provided by drought stress for seedlings are likely offset by growth and productivity reductions.
- Southern pines typically do not show visible symptoms of ozone injury under ambient O_3 conditions, but growth of mature southern yellow pines is being reduced by current ambient ozone levels at annual rates that vary from 0 to 10 percent per year.
- Continued increases in ozone concentrations will likely have significant negative impacts on pine forests in the South.
- Forest area and growth rates could increase across the South with moderate increases in air temperatures and carbon dioxide concentrations during the 21st century. Severe temperature increases could negatively affect forest productivity and area, especially if precipitation rates do not increase to compensate for increased water demands.
- Carbon storage in southern forest ecosystems, including public, private, and industrial

forests , could make a significant contribution to carbon sequestration. Future policies, incentive programs, and forest management intensity will affect carbon sequestration rates.

- Land-use change, not climate change or atmospheric chemistry, has been and probably will continue to be the most important determinant of carbon storage, uptake, and release in terrestrial ecosystems.

- Existing climate change models do not provide adequate information to forecast changes in location, extent, frequency, or intensity of extreme weather events and their impacts on forest ecosystems. Potential increases in air temperature and changes in precipitation patterns may contribute to increased frequency or intensity of some events.

- Detailed spatial and temporal predictions of abiotic stressor effects on forest sustainability are not possible without long-term improvements in regional monitoring and studies designed to understand specific and integrated broad-scale stress responses at forest ecosystem, community, and species levels.

2 Introduction

The sustainability of southern forests could be threatened by the interactions of biotic and abiotic stressors (McLaughlin and Percy 1999). Environmental factors such as temperature, precipitation, atmospheric carbon dioxide (CO_2) and ozone (O_3) concentrations, and acid deposition affect forest processes such as carbon, water, and nutrient fluxes. These processes are the foundation of forest ecosystems, and abnormally large variability in their size, timing, or location may influence forest sustainability. From an ecosystem perspective, therefore, changes in forest processes may be indicators of long-term forest function and health.

Sulfur and nitrogen deposition have been indicted as contributors to forest degradation, especially in the high-elevation red spruce and Fraser fir forests that occupy the ridges of the Appalachian Mountains (McLaughlin and Kohut 1992). In an effort to manage and sustain spruce-fir and hardwood forests in a way that does not compromise the ability of future generations to meet their needs, the current and future impacts of sulfur and nitrogen deposition on overall forest health in the Southern United States must be addressed.

Ground level (tropospheric) O_3 is an air pollutant that affects U.S. forests (U.S. EPA 1996). At current ambient levels, O_3 can decrease tree growth, increase the probability of mortality, cause visible foliar damage, and alter forest successional patterns (Flagler and Chappelka 1996, McLaughlin and Downing 1995, Teskey 1996). For these reasons, current and projected O_3 impacts on southern forests are addressed in this Assessment.

Climate influences the establishment and growth of forest trees, affecting the extent and quality of forest ecosystems. The spatial and temporal distribution of air temperature and precipitation are the primary climatic factors shaping forests. Human activities contribute significantly to current global climate change (Dale and others 2000), predominantly due to the increasing concentration of greenhouse gases such as CO_2. Since the beginning of the industrial revolution,

CO_2 levels have been steadily increased by fossil fuel burning and land-use changes (U.S. DOE 1999, Sarmiento and Wofsy 1999). Even if changes in CO_2 concentration did not effect climate changes, they would affect plant growth.

Independently developed climate-change scenarios are generated with transient general circulation models (GCMs) that simulate atmospheric dynamics under a gradual doubling in greenhouse gas concentrations from about 1895 to 2100. Emissions of CO_2 to the atmosphere are predicted to increase from 7.4 gigatons/year (Gt/yr) in 1997 to 26 Gt/yr by 2100 (U.S. DOE 1999). For this Assessment, these scenarios are used with ecological process models to investigate the potential effects of climate change on forest ecosystems.

Forest carbon sequestration, the ability of forests to store and release carbon, is currently an important issue debated in the policy arena. Carbon stored in forests affects the amount of carbon contributing to the increasing atmospheric CO_2 concentration. Reductions in carbon emissions have been proposed as a mitigation strategy for rising atmospheric CO_2, which may be causing global warming. Rising atmospheric CO_2 levels could also be mitigated by increasing carbon sequestration through forestry and other land management activities. Terrestrial ecosystems have enormous potential to capture CO_2 and store carbon.

Climate change also could generate forest stress, and extreme weather events cause disturbances that shape forest systems by influencing their composition, structure, and functional processes. We discuss the effects of these disturbances and their relationship to changing temperature and precipitation patterns.

Biotic stressors such as insects and pathogens have major negative impacts on forest ecosystems; in the United States, they cause severe damage on an average of more than 50 million acres per year, costing $2 billion a year (Dale and others 2000). Biotic stressors are the focus of Chapter HLTH-2.

For each of the abiotic stressors, methods, data sources, results, discussion, and conclusions are discussed separately. Current abiotic stressors have been described for different coarse-scale studies. Attempts at regional-scale characterizations and future predictions are underway and are highlighted when feasible.

It is important to recognize the integrated nature of these abiotic stressors and their cumulative effects on forest ecosystems. This integration is referenced throughout the Chapter. It is imperative that readers consider cumulative integrated effects when interpreting the results and conclusions from this Chapter.

3 Acid Deposition

3.1 Acid Deposition Methodology: Current Conditions

Acid deposition occurs when emissions of sulfur dioxide (SO_2) and oxides of nitrogen (NO_x)

react with atmospheric water, oxygen, and oxidants to form acidic compounds. Mild solutions of nitric and sulfuric acids are formed and fall as acid precipitation. Sulfur and nitrogen deposition was first described as a problem in Europe in the early nineteenth century and has been studied extensively in North America since the 1970s (Blancher 1991). Sulfur and nitrogen deposition can impair tree growth in several ways. They can leach calcium and magnesium from soils where base cation stores are very low and the ability of the ecosystems to retain sulfur or nitrogen is minimal (McLaughlin and others 1998). Acid deposition may also involve the release of toxic elements like aluminum from the soil, adversely affecting biological processes and living organisms (Malmer 1976). Nutrient loss and soil degradation have been observed in some hardwood forests (Swank and Vose 1997). However, pine, hardwood, and mixed (oak-pine) forests experience slower losses of base cation nutrients and degradation because of their ability to buffer sulfur and nitrogen deposition. These forests generally have large calcium pools that increase their ability to buffer acid deposition.

There is a wide range of sulfate deposition rates across the South (NADP 2000) (Figure 1). The mean regional sulfate deposition for 1999 was 11 pounds/acre, which is a 13-percent decrease in sulfur deposition from 1994 (NADP 2000). The highest regional sulfur values are in North Carolina and Tennessee (Figure 1).They are produced primarily in industrialized States in the northern part of the South.

Currently, forests in the South are exposed to a wide range of nitrogen deposition rates (NADP 2000) (Figure 2). The mean regional nitrogen deposition for 1999 was 10 pounds/acre, a 10 percent decrease in nitrogen deposition from 1994 (NADP 2000). The highest regional nitrogen values are generally located in the northern part of the South (Figure 2). Their sources are emissions from all 31 States east of the Mississippi River (Nash and others 1992).

For this discussion, the South has been divided into nine forest types according to various factors that include geographic location, precipitation, minimum and maximum air temperature, and soil conditions (more or less sensitive to acid precipitation) (Figure 3). Sensitive soils have low base cation stores, and the ecosystem has a low ability to retain sulfur and/or nitrogen. Less sensitive soils are ones with high concentrations of base cations, high buffering capacity to sulfur and nitrogen deposition, and, normally, nitrogen deficiency. Within the region, the high-elevation spruce-fir forests are most sensitive to sulfur and nitrogen deposition. The least sensitive ecoregions are those covered primarily by hardwood, pine, and oak-pine forests. The sensitivity of a given region to acid precipitation depends on the ability of the rocks and soils to neutralize or buffer the acid. Soils derived from granite, which are low in calcium, are highly sensitive. Soils derived from limestone, which are high in calcium, are much more capable of buffering the acid.

3.2 Acid Deposition Methodology: Future Predictions

Sulfur deposition is a primary contributor to acid deposition that indirectly affects forest decline by leaching base cations from the soil. Therefore, in 1990, Title IV of the Clean Air act set as its primary goal the reduction of annual SO_2 emissions by 10 million tons below 1980 levels (U.S.

EPA 1997a). To achieve these reductions by 2010, the law invoked a restriction on power plants fired with fossil fuels. By 1995, nationwide emissions of SO_2 were reduced by almost 40 percent below their required level. In addition, monitoring sites throughout the United States found statistically significant reductions in precipitation acidity and sulfate concentrations (NAPAP 1998). Attempts to reduce nitrogen deposition were initiated in 1996. Although Title IV initiated a reduction in annual nitrogen deposition, new concentrations are expected to have potential impacts on forests across the South. Modeling future projections and impacts of nitrogen and sulfur deposition on forested ecosystems in the Southern Appalachian Mountains is an ongoing research objective of the Southern Appalachian Mountains Initiative (SAMI).

3.3 Acid Deposition Data Sources

Primary data sources for sulfur and nitrogen deposition were the National Acid Deposition Program (NADP 2000) and cited literature.

3.4 Acid Deposition Results

Although sulfur is an essential nutrient for soil and plant metabolic processes, sulfur deposition can contribute to degradation of soil chemistry (Reuss and Johnson 1986). Long-term increases in soil acidity resulting from sulfur deposition are believed to affect nutrient cycling by leaching nutrients, such as calcium and magnesium (Fenn and others 1988). Research has also shown that sulfur deposition provides the stimulus to mobilize aluminum in soil solutions (Reuss and Johnson 1986). Dissolved aluminum interferes with the uptake of calcium and other root functions (Johnson and others 1991).

Currently, high-elevation spruce-fir forests are the most susceptible to the effects of sulfur deposition (McLaughlin and Percy 1999) because they lack the ability to buffer sulfur deposition and are low in base cation pools. Future rates of sulfur deposition are expected to decrease, which could lead to a reduction in the effects of sulfur deposition on base cations in high-elevation spruce-fir forests. Recent evidence indicates that most Southern Appalachian soils supporting spruce-fir ecosystems are poorly buffered, high in aluminum, and nitrogen saturated (Johnson and others 1991). Nitrogen saturation occurs when ammonium (NH_4) and nitrate (NO_3) are present in quantities that exceed total combined plant and microbial demand. Excess levels of nitrogen have been found to affect soil and plant calcium:aluminum ratios (Johnson and others 1991), cause aluminum toxicity (Shortle and Smith 1988), and decrease calcium uptake and leaching of base cations (McLaughlin and others 1998) in these sensitive forests. A lack of calcium changes the wood structure of spruce and fir and may change the ability of branches to withstand stress (McLaughlin and others 1998). Furthermore, excess levels of nitrogen decrease the rates of some critical functions of soil microorganisms, including decay of forest floor material (Drohan and Sharpe 1997). These effects on forest soils are most dramatic in the sensitive soils under spruce-fir forests. Conversely, in an oak-pine forest in the North Carolina Piedmont, Johnson and others (1995) predict that forest floor nutrient contents will be virtually unaffected by a 50 percent reduction in sulfur deposition over the next 20 years.

Effects of acid deposition on tree growth have been associated with nutrient limitations caused by increases in soil aluminum concentrations. Studies of historical tree-ring chemistry (Bondietti and McLaughlin 1992) have shown that calcium concentrations in stemwood increased as growth increased during the late 1940s and 1950s. However, decreases in tree growth were associated with increases in aluminum:calcium ratios in the wood, suggesting that the availability of calcium was reduced at the same time aluminum concentrations increased. McLaughlin and Kohut (1992) have shown evidence for the competitive inhibition of calcium uptake by aluminum. Dendroecological and plot-based data have shown declines in radial growth of red spruce radial growth decline (LeBlanc and others 1992) and canopy crown deterioration during the mid to late 1980s in the Southern Appalachian Mountains (Peart and others 1992).

While acid deposition has affected tree growth in spruce-fir forests of the Southern Appalachians (McLaughlin and others 1998), damage to these ecosystems is not limited to acid deposition.Reams and Van Deusen (1993) reported that stand disturbances and changes in stand dynamics have resulted in radial growth declines in spruce-fir forests. In addition, the balsam woolly adelgid was introduced into North America at the beginning of the 20th century, and the exotic insect has been active in the Southern Appalachians since the late 1950s (McLaughlin and others 1998). The damage to mature Fraser fir in the Southern Appalachians by the woolly adelgid has been extensive over the past 15 years (Dull and others 1988). Although heavy infestation is unquestionable evidence that the adelgid plays a major role in killing these trees (see the HLTH-2 Chapter for more details), it is also important to consider the influence of predisposing factors, including abiotic stressors such as acid deposition, on the susceptibility of forests to pathogens (Manion 1981).

Hardwood forests in the South are considered less sensitive than spruce-fir forests to nitrogen deposition because they still have adequate stores of base cation nutrients, and the soils still maintain considerable capacity to retain the deposited nitrogen (NAPAP 1998). In most hardwood forests, virtually all nitrogen deposition is either adsorbed in the soil or used by vegetation and microorganisms. Much of this nitrogen may be removed later by forest harvesting. These systems, therefore, have not shown negative effects from increases in nitrogen deposition and may respond with increased growth. Research has shown that 22.8 pounds per acre per year of nitrogen fertilizer increased basal area growth of trees by 67 percent (McNulty and Aber 1993).

Impacts of nitrogen deposition on forest health have not been detected in the pine and oak-pine forests of the South (NAPAP 1998). However, nitrogen is a major contributor to the depletion of base cations in many buffered soils supporting southern pine and oak-pine forests. Over the course of decades, therefore, nitrogen deposition is likely to reduce pine forest productivity (NAPAP 1998). Increases in growth are expected for some nitrogen-deficient soils, while negative effects are expected to be limited to the most acidic soils.

In the future, nitrogen deposition will continue to impact the structure and function of high-elevation spruce-fir forests. In addition, some hardwood, pine, and oak-pine forests that are sensitive to nitrogen deposition could respond with reduced growth rates and accelerated tree mortality over the long term. However, research has predicted that in oak-pine forests in the North Carolina Piedmont vegetation will respond positively to a 200-percent increase in nitrogen deposition over the next 20 years. A 3- to 9-percent increase in vegetation nutrient content and a 10- to 30-percent increase in forest floor nutrient content are expected (Johnson and others 1995).

Currently, the SAMI Class I Wilderness Areas are much more sensitive to acid precipitation than any other areas surveyed by the National Stream Survey (NSS) in the Southern Appalachians (Herlihy and others 1996). The Wilderness Areas of greatest concern are Otter Creek and Dolly Sods in West Virginia. There, the percentage of acidic stream length is high, pH is low, and sulfate and inorganic aluminum concentrations are high. Additionally, stream nitrate concentrations, an indicator of acid deposition effects, have been shown to have a strong correlation with forest age.The highest concentrations occur in old-growth forests, where biological demand for nitrogen is lowest. The Wilderness Area of least concern is the Sipsey, in Alabama, because sulfate concentrations are not increasing and acid neutralizing capacity (ANC) of streams in this area is high.

ANC has been used to determine stream quality because stream acidification affects fish and other aquatic species. Research in the South has shown that the biological response of brook trout can be altered by ANC (Table 1). Furthermore, the Southern Appalachian Assessment has shown that 70 percent of sampled streams have suffered moderate to severe fish community degradation and about 50 percent of the stream miles in West Virginia and Virginia show habitat disruption (SAMAB 1996). However, streams targeted by the NSS in the Southeastern Highlands (which includes the Ozarks/Ouachita, Piedmont, Southern Appalachians, and Southern Blue Ridge and ecological subregions in the states of Arkansas, Georgia, North Carolina, and Tennessee) appear to be buffered from sulfur deposition by a substantial amount of sulfate adsorption in watershed soils (Rochelle and Church 1987). As a result, sulfate concentrations in these streams are low.

3.5 Acid Deposition Discussion and Conclusions

The sources of SO_2 continue to decrease while NO_x emissions remain constant. As a result, plant species structure and composition, soil chemistry, and microbial activities continue to change. Currently, the mortality and decline of Fraser fir and red spruce at high elevations in the Southern Appalachians are the only cases of significant ecosystem damage. Thus, less than 5 percent of the South is currently being negatively impacted by elevated sulfur and nitrogen deposition (Fenn and others 1998). In addition, atmospheric deposition reduces the number of microorganisms important to nutrient cycling and removes important nutrients from the soil, making spruce-fir forests more susceptible to canopy deterioration, drought, loss of foliage, insects, and diseases. Hardwood, pine, and mixed oak-pine forests are less sensitive than spruce-fir for several reasons, including biological nitrogen demand, higher soil cation exchange capacity, and faster nitrogen cycling.

Since most hardwood, pine, and mixed forests are nitrogen-deficient, they may experience increased growth rates in response to continued elevated nitrogen deposition. Conversely, nitrogen deposition can significantly degrade some of these forests over time (years to decades), especially in areas where nitrogen levels may be high and the soil has reached or is approaching saturation.

Sulfate and nitrate concentrations have increased in streams throughout the South, but not to levels that are considered regionally problematic. Furthermore, sulfate and nitrate in some streams are low or near detection limits (Swank and Vose 1997).

3.6 Acid Deposition Needs for Additional Research

To address the indirect impacts of nitrogen and sulfur deposition that lead to soil and vegetation degradation in high-elevation spruce-fir and hardwood forests, continued intensive monitoring, modeling, and validating of acid deposition and nutrient cycling processes must occur across local and regional scales. Monitoring efforts should be supplemented with long-term regional experiments (>5 years) in which realistic acid deposition effects on soil chemical properties and stream quality are evaluated (McNulty and others 1996).

4 Ozone

4.1 Ozone Methodology: Current Conditions

Ground-level O_3 is created through a complex series of atmospheric chemical reactions involving NO_x and volatile organic compounds (VOC) in the presence of specific climatic and weather conditions (Chameides and Lodge 1992). Ozone exposure levels are influenced by factors such as temperature, time of day, relative humidity, windspeed, wind direction, and spatial proximity of anthropogenic and biogenic emission sources (Schichtel and Husar 1999).

Allen and Gholz (1996) revealed extensive spatial and temporal variation in O_3 concentrations across the region. For at least two reasons, accurate prediction of annual variability in O_3 levels for forested areas has not yet been achieved: (1) monitoring sites in rural, forested areas are lacking, and (2) modeling O_3 exposure is very difficult because of weather, and human-related conditions that contribute to its annual variability (Allen and Gholz 1996). However, annual variation in O_3 at select monitoring sites has been analyzed.

Annual O_3 variability for the United States can be seen in Figure 4, which shows 3-month maximum daily SUM06 O_3 exposure levels for 1988 through 1992. A SUM06 value is the sum of all mean hourly daytime O_3 concentrations that are at least 0.06 parts per million (ppm)over a continuous 3-month period (92 days) during the summer. The SUM06 exposure index represents the threshold ambient O_3 level (0.06 ppm-hrs) below which many forms of vegetation can resist harmful cumulative O_3 effects. The SUM06 index may be particularly useful because negative effects of O_3 exposure, especially on tree photosynthetic capacity (Richardson and others 1992) and foliage production and retention (Kress and others 1992), may be cumulative and linear, extending over multiple growing seasons.

4.2 Ozone Methodology: Future Predictions

Over the past century, industrial activity and automobile emissions have increased the atmospheric concentrations of O_3 precursors. As a result, typical ambient O_3 concentrations have increased from 0.02-0.04 to 0.04-0.06 ppm – a trend that is expected to continue into the 21st Century (National Academy of Science 1992). Assuming a 1- to 2-percent annual increase in tropospheric O_3, as estimated by Fishman (1991), the United States will achieve a 50-percent increase in ambient O_3 in 21 (base 1990) years and a doubling of O_3 concentrations in 35 years. The National Academy of Science (1992) estimated an increase of 40 percent by the year 2020. Thompson (1992) used several computer models to predict that O_3 concentrations will rise by 0.5 percent per year for the next 50 years, while Chameides and others (1994) suggested that the frequency of O_3 events with concentrations high enough to damage plants will triple over the next 30 years.

4.3 Ozone Data Sources

Ozone monitoring studies have identified different O_3 exposure profiles at high elevations (>4,900 ft) than at lower elevations (<1,600 ft) and near sea level (Aneja and others 1994). Levels of O_3 in mountains are lower than in lowlands during the daytime. Near sea level, O_3 levels are very high during the day, often exhibiting a distribution characteristic of the peak hours for automobile traffic. The concentrations in the mountainous areas of the South have important implications for forest health. The ambient O_3 concentrations are sufficiently high to induce injury to sensitive native vegetation in the Blue Ridge Mountains (Skelly and Hildebrand 1995). In addition, some areas in the region are downwind of significant NO_x and VOC emission sources. For example, regionally high O_3 levels found in the Blue Ridge Mountains and Shenandoah Valley of Virginia result from a combination of upwind emission sources located in the industrial Midwest and specific weather patterns (Wolff and others 1977). These weather-related O_3 episodes may be attributed to a combination of local and regional-scale factors: (1) higher than normal ambient temperatures; (2) windspeeds and directions associated with stationary high-pressure systems that produce local air stagnation; and (3) lower than normal relative humidity (Aneja and Li 1990).

4.4 Ozone Results

To cause tree damage, O_3 must be absorbed by the plant through the stomatal openings found on the surface of leaves in a process known as stomatal conductance. Stomates open during daylight hours to permit the exchange of gaseous compounds (CO_2, O_2 and water vapor) necessary for photosynthesis. At night, stomates close, preventing the transpiration of water. Because stomates are open during the day, daytime O_3 concentrations are most likely to damage trees. Rates of stomatal conductance vary by species and age, and these rates directly determine both the quantity of O_3 uptake and the plant's response to a given concentration of O_3 (Kelly and others 1995).

It appears that O_3 affects growth and vitality indirectly by predisposing trees to injury from other biotic and abiotic stressors (see review by Chappelka and Freer-Smith 1995). For example, ponderosa pine exhibits increased sensitivity to bark beetle attack in the San Bernardino Mountains following O_3 damage (Cobb and others 1968). In the South, pines typically do not show visible symptoms of O_3 injury under ambient O_3 conditions (see review by Berrang and others 1996) except during extended periods of high O_3 levels, when injury is readily visible.

The amount and way that O_3 affects trees depend on the age of the trees and the species. Given similar amounts of O_3 exposure, immature hardwoods generally exhibit more growth loss than softwoods (Table 2) (McLaughlin and Percy 1999). Based on the limited number of studies available, mature-hardwood growth rates appear to be more sensitive to O_3 exposure than mature-softwood growth rates (Table 2). According to Dougherty and others (1992), an average mature loblolly pine tree growing in a plantation experiences a 3-percent annual loss of gross primary production under ambient O_3 conditions in the South. In a review of 19 studies measuring the influence of O_3 exposure on growth of slash pine, shortleaf pine, and loblolly pine seedlings and saplings, Teskey (1996) concluded that annual growth reductions for pine seedlings in the South were between 2 and 5 percent. For mature loblolly pines, Dougherty and others (1992) used a process model to estimate annual growth reductions of about 3 percent under ambient O_3 concentrations.

Hogsett and others (1997) found that black cherry has strong O_3 sensitivity and tulip poplar has moderate O_3 sensitivity. Southern yellow pine species showed little response to changes in SUM06 O_3 concentrations, and sugar maple exhibited a threshold response in which annual biomass increased dramatically between 26and 38 ppm-hr/yr SUM06.

Overall, it appears that the growth of mature southern yellow pines is being reduced by current typical ambient O_3 levels at annual rates that vary from 0 to 10 percent per year. Annual growth reductions for pine seedlings in the South are probably between 2 and 5 percent (Teskey 1996). However, at present there are no indications of community-level changes (competition dynamics, community structure and function, etc.) attributable to O_3 (McLaughlin and Percy 1999). While O_3 may be reducing annual growth of trees in the South, other air-borne chemicals such as CO_2 and nitrogen and sulfur compounds may be simultaneously increasing growth (see review by Teskey 1996), thereby effectively masking the negative effects of O_3 on overall forest health.

4.5 Ozone Discussion and Conclusions

The growth impacts of ambient O_3 levels on southern pines appear to be statistically significant at this time (see reviews by McLaughlin and Percy 1999, Teskey 1996). Additional increases in tropospheric O_3 will almost certainly have negative impacts on growth of pine species in the South (Teskey 1996).

Another important consideration for future forest health is the frequency and intensity of forest fires. Forest fires produce carbon monoxide, NO_x, and gaseous hydrocarbons that are the precursors of atmospheric O_3 (Bohm 1992). Therefore, forest fires may contribute to O_3 production in wilderness and rural areas (Bohm 1992). Bohm (1992) observed that O_3 has been found to accumulate near the location of a burn and substantial increases in O_3 concentrations (>50 percent above ambient) have been detected downwind of burned areas and at the top of burn plumes.

The important relationship between soil moisture, stomatal conductance and tree sensitivity to O_3 levels highlights the importance of climate in predicting future impacts of O_3 on forest health. Under future climate scenarios, trees in areas of the South characterized by periods of persistent drought and poor soil water storage capacity will be more sensitive to O_3 pollution and will likely incur substantial visible foliar damage (Maier-Maercker 1999).

4.6 Ozone Needs for Additional Research

Because expert predictions identify O_3 as a significant forest stressor well into the 21st century (Heck and others 1998), scientists and policy experts have jointly assessed critical research needs pertaining to effects on forested systems. The Ecological Research Needs Workshop (U.S. EPA 1998) developed one such set of research priorities. A summary of those priorities for forests and natural areas is provided here (Heck and others 1998):

(1) consideration of factors related to scaling results in growth chambers to mature trees, stands, communities, and landscapes;

(2) measurement of selected endpoints (growth, mortality, foliage injury, etc.) in managed and natural ecosystems such as loblolly pine plantations or bottomland hardwood ecosystems across selected O_3 gradients throughout the South, using results to support development of empirical and process-based models designed to understand the mechanisms of plant response to O_3;

(3) determination of utility of using visible foliar injury and other biological indicators to interpret effects of O_3 on specific indices of ecosystem health;

(4) development of economic techniques that measure changes in the value of managed and natural ecosystems affected by O_3;

(5) development of a reasonable O_3 exposure index via defined relationship between O_3 exposure concentration, uptake dose, and selected endpoints (growth, mortality, foliar injury);

(6) study of the interactions between O_3 and other abiotic or biotic stressors.

5 Climate Change and Extreme Weather-Related Events

5.1 Extreme Weather-Related Event Methodology: Current Conditions

Climate effects on forest conditions are most strongly expressed by extreme events such as fire, hurricanes, tornadoes, floods, drought, and ice storms (Dale and others 2000). Each type of event affects forests differently; some cause large-scale tree mortality, whereas others, such as ice storms, impact community structure and organization without causing massive mortality.

5.1.1 Wildfire

The frequency, seasonality, size, intensity, and type of wildfires depend on weather phenomena and forest structure and composition. Fire initiation and spread also depend on fuel availability, the presence of ignition agents, and topography.

Across the Southern Coastal Plain, forest shrub and brush species can create highly flammable fuel conditions in just 5 years under the right climatic conditions, if fuel loads are not managed. Fuel management, therefore, is necessary. Each year, across all land ownership classes, 5.4 million acres are managed with prescribed fire. Seventy-five percent of the prescribed burning occurs in the States of Alabama, Florida, and Georgia. All 34 national forests in the region have prescribed fire programs, and since 1944, approximately 21 million acres have been treated to minimize wildfire risk (Forest Health Protection Program 2000). Fire management would be more prevalent were it not for smoke problems associated with controlled burns. Criteria included in the Environmental Protection Agency's National Ambient Air Quality Standards for Particulate Matter (U.S. EPA 1997b) limit the amount and extent of prescribed fire programs, because smoke can impair road visibility and breathing in sensitive individuals.

Wildfire can substantially influence forest structure and function. Ecological effects of forest fires include mortality of individual trees, shifts in successional direction, induced seed germination, acceleration of nutrient cycling, death of seeds stored in the soil, changes in surface-soil organic layers and underground plant root and reproductive tissues, volatilization of soil nutrients, and increased landscape heterogeneity (Whelan 1995). As a result of these effects, the capacity of forests to provide wildlife habitat, timber, and recreation may be diminished (Flannigan and others 2000).

5.1.2 Hurricanes

Hurricanes disturb forests along the coastlines of the South. Ocean temperatures and regional weather influence the path, size, frequency, and intensity of hurricanes (Emanuel 1987). An average of two hurricanes strike land every 3 years in the United States (NOAA 1997). Some scientists have hypothesized that hurricane impacts on forests, including mortality, may be related to soil characteristics (Duever and McCollum 1993).

5.1.3 Tornadoes

Tornadoes are one of the most important agents of abiotic disturbance in eastern deciduous forests. Nearly 1,000 tornadoes occur each year in the Conterminous United States (Peterson 2000). In the South, tornadoes are very common in Oklahoma and Texas and frequent in Alabama, Florida, Louisiana, and Mississippi. Tornadoes can cause severe mortality, reduce tree density, alter stand size structure, and modify local environmental conditions via soil erosion or nutrient loss (Dale and others 2000). The resulting disturbance may bring about the release of advance regeneration, seed germination, or accelerated seedling growth (Peterson and Pickett 1995). These effects can change gap dynamics, successional patterns, and other ecosystem-level processes such as water use. The relationship between wind strength and severity of disturbance varies by tree species and forest type. Shallow-rooted species and thinned stands tend to be more vulnerable, but multiple factors influence tree response to windstorms.

5.1.4 Floods

Floods occur throughout the South but are most concentrated in coastal and floodplain areas. On average, floods cause almost $4 billion dollars in damage each year (NOAA 2000). Upland forest ecosystems that experience flooding respond with reduced photosynthetic rates; over extended periods, changes in tree species composition are possible, as some species are more flood-tolerant that others (Burke and others 1999, Iles 1993). Most trees can withstand 1 to 4 months of flooding duration without significant injury (Bratkovich and others 1993). In extreme situations, higher mortality rates may occur (Iles 1993). Anaerobic soil conditions in flooded areas cause physiological stress and influence nutrient availability (Burke and others 1999). Secondary effects of flooding include elevated soil erosion and sedimentation rates (Iles 1993). At the regional scale, there is high variability in the spatial location and amount of disturbance associated with floods.

5.1.5 Drought

Droughts occur in most forest ecosystems in the South. Occurrence is irregular in forests east of the Mississippi River, occasional across most of the South, and more common in late summer on the Coastal Plain (Hanson and Weltzin 2000). Consequences long-term drought or, flooding are generally proportional to the area affected; during the past few decades, an increasing portion of the United States has experienced either severe drought or flooding (Karl and others 1995b). Drought effects are influenced by soil texture and depth, exposure, species composition, life stage, and the frequency, duration, and severity of drought. The immediate response of forests to drought is to reduce water use and growth. Small plants, including seedlings and saplings, are usually the first to succumb to moderate drought conditions. Deep rooting and stored carbohydrates and nutrients make large trees susceptible only to severe droughts (Dale and others 2001).

5.1.6 Ice Storms

Ice storms occur throughout the South. They are produced when rain falls through subfreezing air masses, freezing when contact is made with objects on the ground. Ice accumulation varies with topography, elevation, and area of exposure. Ice storms may sever twigs and bend or break stems, causing moderate crown loss. Damage to forest stands can range from light and patchy to the breaking of all mature stems, depending on stand composition, past disturbances, and the amount of ice accumulation (Irland 2000). Effects of ice storms on forest stands include stem damage, loss of growth until leaf area is restored, and possible shifts in tree species composition towards trees more resistant to ice damage.

Recently thinned stands may have increased vulnerability to ice storm damage, because tree crowns have spread into openings but branch strength has not increased yet. Potentially, there are several secondary consequences of ice damage. Susceptibility to insects and diseases may be increased, and fuel loads may accrue, heightening wildfire risk in some areas (Irland 2000).

5.2 Climate Change Methodology: Future Predictions

The effects of climate change on southern forest productivity and hydrology across a range of climate and site conditions were assessed with the well-validated, physiologically based forest process model PnET-II (McNulty and others 2000). PnET-II used four monthly climate variables (minimum air temperature, maximum air temperature, precipitation, and solar radiation), forest type-specific vegetation parameters, and site-specific soil water holding capacity to predict forest growth and drainage across the South at a 0.5 by 0.5 degree (approximately 30 by 30 mile) spatial resolution. Atmospheric CO_2 increases were incorporated into PnET-II by entering the relationship between water use efficiency (WUE) and CO_2 level. PnET-II results for pine and hardwood forest types have been validated for the South (McNulty and others 2000).

Impacts of climate change on forest area, distribution, and biodiversity were studied with biogeography models. This type of model uses resource and ecophysiological constraints such as available soil water and minimum winter temperatures to simulate climate change impacts on forest ecosystems at regional, continental, and global scales (Bachelet and Neilson 2000). The biogeography models used here predict the dominance of different plant species under different climatic and environmental scenarios. The several biogeography models used for this Assessment included the Mapped Atmosphere Plant Soil System (MAPSS), BIOME3, and MC1 (Bachelet and Neilson 2000; Bachelet and others 2001). Input datasets include latitude, mean monthly temperature, windspeed, solar radiation, and soil properties such as texture and depth. All of these models project vegetation responses to changes in CO_2, but through different mechanisms.

5.3 Climate Change and Extreme Weather-Related Event Data Sources

To date, it is generally believed that higher and more extreme daily air temperature will occur across the United States in the future (NAST 2001). However, the timing and distribution of precipitation or other weather phenomena are much less certain (Dale and others 2000). The transient climate change scenarios used for this Assessment do not adequately represent extreme events because of their coarse spatial and temporal resolution (monthly time step, approximately 1,000 square miles) (NAST 2001). Extreme events may last only minutes or days, and their extents may range from local to small regional scales. When effects of extreme events are averaged over large periods of time and space, much information is lost. Therefore, very little quantitative data on extreme weather events are available to predict future forest impacts. Instead, we will discuss the potential impact of projected general trends in extreme weather events on forest structure and function.

Two climate datasets developed by the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) were used with the PnET-II model to assess future climate impacts on southern forest growth. The Historical Climate Series includes monthly and daily climate data with interannual variability for the Conterminous United States from 1895 to 1993 (NAST 2001). The Hadley Centre HadCM2Sul transient climate change scenario was used to represent climate variables from 1994 to 2100; other climate scenarios exist but were not available at the time of this analysis. For the Continental United States, the HadCM2Sul scenario includes a relatively modest 2.8° average increase in air temperature, a 20 percent average increase in precipitation, and effects of doubled CO_2 and altered sulfate aerosol concentrations (based on IPCC projections of future greenhouse gases) by 2100 (Bachelet and others 2001). The mean temperature increase for the South is about 1.0° by 2030 and 2.3° by 2100; this degree of warming is smaller than that of any other region (NAST 2001). This scenario predicts that the South will remain the wettest region for the next century; mean annual precipitation increase will be about 3 percent by 2030 and 20 percent by 2100. Other regions in the Eastern United States are predicted to experience similar increases in precipitation (NAST 2001).

Predictions of forest area, distribution, and biodiversity used four equilibrium (UKMO, GISS, GFDL-R30, OSU) and three transient (HadCM2Sul, HadCM2GHG, CGCM1) climate scenarios as input for the MAPSS biogeography and MC1 dynamic global vegetation models. The range in temperature increase is 2.8 to 6.6° for all scenarios, with changes in precipitation varying greatly between the scenarios, and changes in CO_2 transient (as with HadCM2Sul) or instantaneously doubling in the case of the equilibrium scenarios. MC1 used only HadCM2Sul and CGCM1, while MAPSS used all equilibrium scenarios and averaged the last 30 years of the transient scenarios so they could be treated as equilibria. The BIOME3 model used only the transient climate scenarios (Bachelet and Neilson 2000).

5.4 Climate Change and Extreme Weather-Related Event Results

5.4.1 Wildfires

Because climate change may alter the frequency, intensity, distribution or extent of wildfires, species regeneration patterns may be disturbed, with species or communities at the edges of their natural range experiencing potentially severe effects.

Model results from the fire distribution module of MC1 predict great variation in future fire-weather patterns for the northern portion of North America (Bachelet and Neilson 2000). The seasonal severity rating (SSR) of fire hazard increases over much of North America under both the HadCM2Sul and the CGCM1 scenarios. The wetter HadCM2Sul scenario predicts smaller (<10 percent) increases in SSR by 2060 for most of the United States. The warmer and drier CGCM1 scenario produces a 30-percent increase in SSR for the South. Expected increases in area burned in the Unites States are between 25 and 50 percent by 2060, with most of the increase occurring across the South and in Alaska (Flannigan and others 2000).

In addition, recent results from the MC1 model, described by Neilson and Drapek (1998), show increases in biomass burned. This model includes an interaction with CO_2 and increased WUE that produces more biomass and thus more fuel, contributing to more and larger fires under a highly variable climate having dry years interspersed with wet periods.

5.4.2 Hurricanes

Global climate change may speed up the hydrologic cycle by evaporating more water, transporting that water vapor to higher latitudes, and producing more intense and possibly more frequent storms (Royer and others 1998, Walsh and Pittock 1998). Hurricane formation could be influenced by changes in temperature and the global hydrologic cycle, but neither the magnitude nor direction of the change can be predicted at this time. Sea-surface temperatures (SSTs) are predicted to increase, with warmer SSTs expanding to higher latitudes (Royer and others 1998, Walsh and Pittock 1998). Even if hurricane frequency does not increase, the intensity and duration of storms may increase with air and ocean temperatures, which are energy sources for hurricanes (Walsh and Pittock 1998).

5.4.3 Tornadoes

Berz (1993) suggested that the frequency and intensity of tornadoes (and hailstorms) might be accelerated with increased intensity of atmospheric convective processes. Karl and others (1995c) found that the proportion of precipitation occurring in extreme thunderstorms has increased in the United States from 1910 to 1990, and their research suggested that precipitation and temperature anomalies have become extreme in recent decades (Karl and others 1995a). The thunderstorm conditions that contribute to tornado formation have increased, and this trend is expected to continue with projected changes in climate. It can be inferred from this relationship that warmer temperatures will increase tornado frequency. Despite the data on thunderstorms and the indirect inferences about tornado frequencies, the understanding of tornado genesis is still inadequate for forecasting climate change impacts on tornado frequency or severity in the coming decades.

5.4.4 Floods

Climate change predictions include increased frequency of heavy precipitation events and severe flooding (IPCC 1998). From 1987 to 1997, there were ten times as many catastrophic floods globally than in the previous decade (Hileman 1997).

Over the last century, sea level has risen 3 to 10 inches. Predicted increases in global air temperatures may result in sea level rises of 15 to 25 inches by 2100 (Gornitz 2001). Current trends in sea level have been confirmed to be higher than those found in long-term geologic records (Gornitz 2001).

5.4.5 Drought

Global circulation model predictions of future precipitation patterns are particularly problematic for the South. While the HadCM2Sul scenario predicts increased precipitation throughout the United States, a Canadian Centre for Climate Modelling and Analysis GCM, CGCM1, predicts significant reductions in both summer and winter precipitation across the South by 2100. To address the potential impacts of drought on forests, the net effect of precipitation changes on soil water must be understood; unfortunately, global scale climate models are not designed to predict this information (Hanson and Weltzin 2000).

5.4.6 Ice Storms

Unfortunately, there is no consistent historic record of ice storms over broad scales with rigorous measurements of ice accumulation. Neither are historical data on climatology associated with ice storms sufficient to correlate past storm frequency and severity with past climate changes. Effects of future climate change on location, extent, and impacts of ice storms, therefore, are also unknown (Irland 2000).

5.4.7 Climate Change

Southern forest productivity, as predicted by the PnET-II model and the HadCM2Sul climate scenario, is shown in Figure 5, Figure 6, and Figure 7 for the decades centered on 2000, 2040, and 2090. Predicted productivity increased by 12 percent from 2000 to 2100 (NAST 2001). Changes in forest productivity resulting from climate change were different for hardwood and pine forest types. By 2040, hardwood and mixed pine-hardwood forest productivity increased by 22 percent, while plantation pine forest productivity increased by 11 percent. By 2100, hardwood and mixed pine-hardwood forest productivity increased by 25 percent, and plantation pine forest productivity increased by 8 percent (NAST 2001). A review of over 50 studies found an average increase in plant dry mass of 32 percent under a doubling of CO_2 concentrations. WUE, examined in another review, increased between 30 and 40 percent (IPCC 1998).

Both MAPSS and MC1 models predict that moderate temperature increases produce increased vegetation density and carbon sequestration across most of the United States small changes in vegetation types result. If temperature increases are more severe, the models predict shifts in vegetation types and reductions in carbon storage. The South is predicted to have expanded forest area (national average of 20 percent) under the more moderate climate scenarios but forest decline under more severe climate scenarios (including CGCM1), with catastrophic fires potentially causing rapid vegetation conversion from forest to savanna (Figure 8) (Bachelet and others 2001). MC1 predicts a return to forest by the end of the 21st century, albeit with lower forest biomass than before the fires occurred. The same moderate-increase, severe-decrease trend is true for leaf area index (LAI), a measure of leaf area per unit of ground area, and vegetation density of forests in the South. MAPSS and MC1 predict an increased presence of tropical forests along the Gulf Coast (Bachelet and others 2001).

5.5 Climate Change and Extreme Weather-Related Event Discussion and Conclusions

5.5.1 Wildfire

The rapid response of fire regimes to changes in climate can potentially overshadow the direct effects of climate change on species distribution, migration, or extinction (Flannigan and others 2000, Stocks and others 1998).

5.5.2 Hurricanes

The effects of hurricanes on forest vegetation include sudden, massive, and complex patterns of tree mortality and altered patterns of forest regeneration (Lugo and Scatena 1996). A likely result is lower aboveground biomass in mature stands (Lugo and Scatena 1995). Faster rates of decomposition and vegetation regrowth have been measured after hurricanes; species substitutions, with those species having faster nutrient and biomass turnover rates becoming more competitive, may result (Lugo 2000). Hurricanes can also bury vegetation in carbon sinks, increasing below-ground carbon storage (Dale and others 2000, Lugo 2000). Overall, it has been suggested that the decadal variation in hurricane intensity and frequency may be great enough to mask any changes resulting from climate change (Lugo 2000).

5.5.3 Tornadoes

Damage resulting from tornadoes may shift forest species composition towards late-successional species, as early-successional species often are large and shallow-rooted, making individuals more vulnerable. Because late-successional species may share these traits, effects of tornadoes or other catastrophic winds on species composition may be more contingent on forest species and size characteristics (Peterson 2000). Wind disturbances often remove dominant trees from the forest, changing species richness or evenness and potentially altering species diversity (Peterson 2000).

5.5.4 Floods

It is difficult to translate changes in precipitation patterns to effects on flood probability or severity. Existing flood records suggest that monitoring runoff and streamflow levels may provide more insight on future floods (IPCC 1998).

At predicted levels of increase, sea level rise would threaten coastal areas with more frequent flooding, salinization of coastal streams and aquifers, and increased beach erosion. It is important to consider that local sea levels are also affected by regional processes such as ocean tides and currents (Gornitz 2001).

5.5.5 Drought

Secondary effects of drought may occur. When reductions in growth are extreme or sustained over multiple growing seasons, increased susceptibility to insects or disease is possible, especially in dense stands (see Negron 1998). Drought may also reduce decomposition rates, leading to a buildup of organic matter on the forest floor. This buildup may reduce nutrient cycling or increase fire frequency or intensity.

The consequences of drought depend on annual and seasonal climate changes and the ability of current drought adaptations to provide resistance or resilience to new conditions. Forests are likely to grow to a level of maximum leaf area, using nearly all the available soil water in the growing season (Neilson and Drapek 1998). A significant increase in growing-season temperatures could increase evaporation and trigger moisture stress.

If changes in regional precipitation reduce soil moisture, there may be direct impacts on plant foliage water status that modify carbon assimilation (Hanson and Weltzin 2000).

Overall, reductions in total annual rainfall would not increase drought severity in most forests of the South because early-season rainfall is the most important determinant of total growth (Hanson and Weltzin 2000). However, there are different responses to late-season drought for hardwoods and pines of the Eastern United States. Hardwood growth activity does not overlap with drought occurrence and therefore basal area growth is relatively unaffected. Because conifer stems grow during a greater portion of the growing season, their drought susceptibility is greater (Hanson and Weltzin 2000).

5.5.6 Ice Storms

Though the weather conditions producing ice storms are well understood, it is uncertain how climate change will influence the frequency, location, extent, or intensity of these extreme weather events. Jagger and others (1999) state that warmer winter temperatures brought about by climate change may increase the probability of ice storms across portions of the United States. Continued atmospheric warming will likely shift the distribution of ice storms northward, potentially decreasing the frequency and severity of ice storm damage to southern forests (Dale and others 2000, Irland 2000).

5.5.7 Climate Change

According to the PnET-II and HadCM2Sul predictions, forest productivity increased more for hardwood and mixed pine-hardwood forest types than for pine plantations. The primary reason for this conclusion is the greater annual water demands of pine forest types. Even with increasing WUE resulting from increasing atmospheric CO_2, evapotranspiration rates increase with air temperature, and pines are still water-limited under the HadCM2Sul climate scenario. Sensitivity analyses completed for PnET-II and the HadCM2Sul scenario showed that substantial variation in temperature increase may lead to larger net losses in forest area and productivity (NAST 2001).

Elevated CO_2 influences tree physiology, potentially increasing productivity, WUE, and nutrient (nitrogen) use efficiency. Reviews of CO_2-enrichment studies have shown positive but variable biomass accumulation. Interactions between CO_2 and other environmental factors account for some of the wide response range (NAST 2001). For example, in a recent North Carolina field experiment, growth of loblolly pine increased by 25 percent under continuous CO_2 elevation (NAST 2001). Maintaining such responses on a decadal time scale could mean greater carbon storage potential and increased drought tolerance. For some species, however, acclimation to increased CO_2 levels has included a reduction in photosynthesis (IPCC 1998). Such down regulation may occur when nutrient availability does not increase with CO_2 (NAST 2001). Recent studies point out that acclimation to CO_2 may not be as widespread when roots are unconstrained, and that leaf conductance may not be reduced. In this case, forests might produce more leaf area under elevated CO_2, but because transpiration could also increase under increased temperatures, soil drying and drought effects could result (IPCC 1998).

If precipitation patterns decrease across the region, rates of evaporation and transpiration could increase without offset, resulting in declines in runoff and consequent drops in river flows, groundwater levels, and recharge. Alternatively, if substantial increases in precipitation occur, increases in runoff and river flows could be expected (IPCC 1998).

Wetlands may be particularly affected by variability in the amount and seasonality of rainfall. As a result, flood protection, water filtering, carbon storage, and other wetland functions may be significantly altered (IPCC 1998).

Results from the biogeography models suggest a northward shift in forest productivity over the next century, but they do not consider changes in management that could potentially ameliorate adverse effects. In summary, forest productivity in the South will likely increase over the next century as a result of atmospheric CO_2 enrichment, provided (1) precipitation and temperature changes do not offset the enrichment benefits by inducing water stress and (2) abiotic stressors such as O_3 do not reduce growth rates significantly. Strategies to increase WUE or water availability could be used to prepare for a potentially warmer and drier climate.

5.5.8 Interactions between climate, extreme weather-related events, and forest health

Disturbance effects often cascade. Drought may weaken tree vigor, leading to insect and disease infestations, or fire. Disease and insect infestations promote future fires by increasing fuel loads. Fires then promote future infestations by compromising tree defenses.

Changes in forest management, land use, and atmospheric chemistry interact with natural disturbances. For example, in the Southern Appalachian Mountains, climate change, increased O_3 exposure and acid deposition, and infestations of non-native insects may increase stress and mortality in red spruce and Fraser fir forests. In some combinations, negative impacts from disturbances may be ameliorated: under drought conditions, leaf stomata tend to close, reducing the effects of elevated O_3 exposure on seedlings (McLaughlin and Percy 1999).

Interactions between extreme weather events are common in the South. The impact of multiple extreme events is greater than the sum of the individual events (Paine and others 1998). For example, although hurricanes rapidly lose strength after reaching land, sustained winds of over 40 miles per hour may occur hundreds of miles inland. Soil saturation, which occurs when large amounts of rain accompany the winds, can reduce tree root support. Under these conditions, even a moderate wind can blow down a mature tree. Without these multiple stresses, little or no forest damage would have occurred.

Interactions between extreme weather events are further complicated by the effects of other forest ecosystem stressors. Drought often weakens tree vigor, increasing the potential for insect or disease attacks. If tree mortality results from these combined stresses, fuel loads and the likelihood of future wildfires can also increase. An example of interactions of this type can be observed in the Southern Appalachian Mountains, where increased O_3 exposure and periodic drought have increased the infestation rate of native and non-native insects in red spruce and Fraser fir forests. The combined stressor effects are partially responsible for increased mortality in these high-elevation tree species. Climate change may cause these integrated events and their compounded influences to occur slowly, unpredictably, and in unique configurations.

Understanding the effects of climate change on extreme weather events is critical for managing broad-scale disturbances before, during, and after they occur. Forest management could play a key role in minimizing negative forest responses, thus sustaining forests through long-term climate change and short-term intense weather events.

5.6 Climate Change and Extreme Weather-Related Event Needs for Additional Research

To project climate change and variability at a regional scale, increased spatial resolution in long-term climate change scenarios is needed. Precipitation predictions for the South are particularly problematic; different climate scenarios simulate large differences in precipitation pattern changes over the next century. This uncertainty forces regional assessment developers and users to consider a wide range of potential futures.

There is a limited understanding of climate change impacts on extreme weather events. Multiple stressors and their regional-scale integrated effects are critical areas for future research. As these phenomena are measured and understood, broad-scale forest ecosystem monitoring programs should be implemented to provide continuous, current information on forest conditions and to allow for the validation of modeling results.

In field chamber experiments, co-exposure to increased CO_2 and O_3 has been shown to offset predicted gains in forest growth from elevated CO_2 and to increase damage from O_3. More research is needed to consider the combined effect of these gases (McLaughlin and Percy 1999).

6 Carbon Sequestration

6.1 Carbon Sequestration Methodology: Current Conditions

Forest carbon is generally reported in terms of carbon in above- and below-ground tree components, understory vegetation, forest floor litter, and soil; with over 90 percent stored in the tree and soil components (Plantinga and others 1999). The carbon cycle involves carbon fluxes between the atmosphere, oceans, and terrestrial biosphere, with active reserves transferred through biological, physical, and chemical mechanisms (Sarmiento and Wofsy 1999). Processes that naturally increase the emission of CO_2 have historically been balanced by processes that accelerate carbon sequestration, thus resulting in little change to atmospheric CO_2 levels (U.S. DOE 1999). The current large increase in atmospheric CO_2, however, implies that CO_2 emissions exceed carbon sequestration (U.S. DOE 1999).

6.1.1 Forest Structure and Land Use

Forests contain approximately 85 percent of global aboveground carbon (Huntington 1995); however, the relationship between carbon sequestration and forest structural characteristics is complex. On average, regenerating southern forests initially act as net carbon sources, but generally become carbon sinks within 10 to 15 years due to rapid carbon accumulation (Figure 9). Carbon accumulation continues to increase until stands reach maturity. After this time, net carbon uptake begins to decrease and may approach zero (Plantinga and others 1999). Site differences (including climate, topography, and soil) greatly influence the forest productivity and carbon sequestration potential of an area. These differences are further enhanced when considering previous land use practices and their effect on soil fertility. Land use change, not climate change or atmospheric chemistry, has been and probably will continue to be the most important determinant of carbon storage, uptake, and release in terrestrial ecosystems (Sampson and others 1993).

6.1.2 Forest Soils and Long-Term Carbon Sequestration

Forest soils appear to be the best available long-term option for storing carbon in terrestrial ecosystems because the residence time of carbon in soils is much longer than in aboveground biomass (U.S. DOE 1999). Approximately 50 to 60 percent of the carbon in temperate forest ecosystems is found in the soil organic matter (SOM)(U.S. DOE 1999, Huntington 1995). Soils with high concentrations of carbon in SOM have improved nutrient absorption, retention, and resistance to erosion (U.S. DOE 1999), factors especially important for forest productivity and carbon sequestration (U.S. DOE 1999, Johnson 1992). However, understanding and quantifying soil carbon pools has been complicated by a lack of available data (Huntington 1995, Sanchez 1998). For example, temperature is an important controller of soil organic carbon dynamics, but the effects of different temperature scenarios on soil carbon are not fully understood (Garten and others 1999).

Land management practices and land use changes can directly affect the ability of soils to sequester carbon. Practices that protect soil and reduce erosion greatly improve the potential of those soils to sequester carbon (U.S. DOE 1999). Comparing disturbed (previously harvested) and relatively undisturbed (no known cultivation or harvesting since European settlement) watersheds in Georgia, Huntington (1995) found that disturbed sites have potential for large increases in soil carbon storage. Harvesting followed by cultivation also results in substantial losses of SOM; intensive cultivation after forest harvesting can cause SOM to decrease by 50 percent in the upper 7.87 inches of soil (Huntington 1995, U.S. DOE 1999). This practice can also result in overall soil carbon losses of 30 to 60 percent (Huntington 1995). Converting cultivated land to forests, on the other hand, provides an important carbon sink. There are clearly opportunities to increase carbon storage in soil through reforestation of former agricultural land and adoption of forest management practices like fertilization and genotype improvement that increase net rates of biomass production (Johnson 1992). Timber harvesting followed by forest regrowth does not necessarily reduce soil carbon storage (Huntington 1995) and may increase soil carbon storage (Johnson 2001). When followed by erosion and subsequent loss of SOM, however, harvesting does result in substantial losses of soil carbon and fertility. Harvesting practices may increase soil carbon when specifically designed to do so, by burying forest floor material and downed dead wood in the soil. At the broad scale, while soil fertility losses may be partially mitigated by increases in CO_2 and nitrogen deposition, air and water pollution may lead to soil degradation and further carbon loss (Huntington 1995, Sarmiento and Wofsy 1999).

6.1.3 Long-Term Carbon Storage in Harvested Wood

Harvested wood provides options for long-term carbon storage and, when burned, a substitute for non-renewable fossil fuel-derived emissions (Heath and others 1996, Skog and Nicholson 1998). Carbon can be stored for centuries in furniture or housing. When discarded in anaerobic landfills like those currently used in the United States, wood stores carbon for long periods.

6.2 Carbon Sequestration Methodology: Future Predictions

Given the large quantities of SOM lost through erosion and cultivation, it is not known if soil carbon will be able to return to predisturbance levels (Huntington 1995). Indications for the forested Piedmont, including reforested abandoned agricultural lands, are that the rate of sequestration will begin to slow later this century as soil carbon approaches predisturbance levels, thus reducing the potential of these soils to sequester additional carbon (Huntington 1995). Whether forests are managed for maximum sustained yield of biomass or maximum financial return, they will rarely contain more than approximately one-third of the carbon stored in a forest grown to maximum biomass (Cooper 1982).

6.3 Carbon Sequestration Data Sources

The current and potential carbon storage and flux of actual vegetation have been examined in the United States using data from the USDA Forest Service Forest Inventory and Analysis databases (Miles and others 2001) and models such as FORCARB (Heath and Birsey 1993, Plantinga and Birdsey 1993). FORCARB provides historical estimates and projections of carbon in forest ecosystems and harvested wood; an explanation of the uncertainty associated with FORCARB projections can be found in Heath and Smith (2000). Baseline carbon sequestration projections are based on preliminary results from the updated work of Haynes and others (1995).

6.4 Carbon Sequestration Results

Average aboveground carbon in southern forests is approximately 25 tons/acre (Figure 10). Higher averages are found in the Appalachian Mountains and the Mississippi Alluvial Valley. Over the last 40 years, increases in biomass and organic matter on U.S. forest lands have added only enough stored carbon to offset 25 percent of national emissions for the same period (Birdsey and Heath 1997). This result has important implications since the overall carbon inventory in southern forests is predicted to remain relatively stable through 2040 (Figure 11).

Non-industrial private forests store more total aboveground carbon than all public and industrial lands combined, due to a much higher percentage of forest land being privately owned (Table 3). Approximately 42 percent of the aboveground carbon in southern forests is in the oak-hickory forest type group (Table 4), which dominate non-industrial land (Table 5). While the percentage of the oak-hickory forest type group is expected to decrease slightly by 2020, it will continue to dominate non-industrial private forests (see Chapter TIMBR-2 for more information). Volume and stocking density measurements on these tracts indicate that they are typically understocked and managed with low intensity (NRC 1998). Private landowners could make a significant contribution to carbon sequestration efforts by increasing stocking levels.

Southern pines dominate southern industrial forests due to their fast growth and high product value, and therefore make up over 60 percent of all forest industry and Timber Investment Management Organization forestland (see Chapter TIMBR-2 for more information). This proportion is predicted to increase by 10 to 20 percent by 2020 (Table 5). Since intensive management strategies have been shown to increase planted pine yields 70 percent more than traditional management (see Chapter TIMBR-2 for more information), manipulating commercial sites will be an important carbon sequestration tool.

In the South, harvesting forests initially results in a net carbon loss, but sites begin to show a net carbon gain 10 to 15 years after harvest. Most of the carbon in harvested wood is either lost through emissions, stored in finished products, or burned for energy as a substitute for fossil fuels. Residual wood left on site decays and returns to the soil or goes off to the atmosphere as CO_2. Waste and discarded products are buried in landfills where the carbon continues to be stored. Figure 12 shows an example of the estimated disposition of carbon on a highly productive southeastern pine site after 80 years, with a rotation age of 40 years. While 53 percent of the carbon sequestered in trees is lost in emissions and energy (wood burned as a substitute for fossil fuels), 39 percent of the carbon remains stored in products and landfills. Since the total amount of carbon in wood removed from southern forests is expected to increase between now and 2035 (Figure 13), high levels of emissions could continue to counteract carbon sequestration efforts. However, the emissions should be estimated carefully because burning wood for energy mitigates fossil fuel emissions.

6.5 Carbon Sequestration Discussion and Conclusions

Despite many volumes of research detailing individual tree responses to elevated CO_2 and tree stresses, the complexity of ecosystem interactions has made it difficult to understand and predict whole system responses. Currently, there is very little understanding of the relationship between carbon sequestration and species composition and interactions among CO_2, O_3, nitrogen, temperature, and precipitation (Aber and others 2001). The long-term impacts on manipulated sites are not completely understood. Consideration of site characteristics and past land use should be an important component of forest sustainability and carbon sequestration research. Maximizing carbon per acre on all land will be an important step toward increasing long-term carbon storage.

The lack of understanding of interactions in forest processes results in uncertainty when estimating current and future carbon budgets. Uncertainty is defined by Smith and Heath (2000) as the inability to precisely quantify an unknown, but unique, inventory of carbon in a given forest management unit for a particular year. Uncertainty can be minimized through multi-site, multi-factorial experiments; but the costs, time constraints, and logistics involved limit the feasibility of such an approach (Aber and others 2001). It will be important to understand both the trends and uncertainties in carbon pool estimates when making policy decisions (Aber and others 2001). Until we have a greater understanding of carbon flows and the potential interactions involved, research should be aimed toward identifying areas that will contribute most to reducing overall uncertainty (Heath and Smith 2000).

Increases in anthropogenic CO_2 emissions and the possible resulting global warming have created the need for increased carbon sequestration in forests and harvested wood. Current southern forest carbon inventory is approximately 5.5 billion tons in trees alone (Birdsey and Heath 1995). While additional research is required to further understand carbon fluxes, it is clear that southern forests offer an enormous opportunity for capturing CO_2 and storing it as carbon while still providing wood products and other benefits. Future policies involving incentive programs and forest management intensity are factors that will potentially affect carbon sequestration rates. It should be acknowledged, however, that land use change, more so than changes in climate or atmospheric chemistry, has been and will likely continue to be the most significant determinant of terrestrial carbon storage, uptake, and release.

6.6 Carbon Sequestration Needs for Additional Research

Future research and measurement must focus on long-term storage of carbon in forests, specifically in soils, forest floor material, aboveground biomass, and harvested wood. The potential for substituting wood fuel for fossil fuel needs additional review. Information about methods to assess site differences, the influence of previous land use practices, management methods that could be adopted to increase carbon storage, and responses to potential climate change scenarios will also be crucial to understanding the ability of forests to sequester carbon.

7 Conclusions

This Assessment highlights the integrated nature of abiotic factors that cumulatively affect overall forest health. Acid deposition does not pose a significant threat to southern forest vegetation except in the Southern Appalachian Mountain high-elevation spruce-fir forests. Nitrogen-limited forests may respond to continued nitrogen deposition with increased growth rates. Acid deposition is not causing significant damage to stream chemistry in the South. However, areas in the Southern Appalachian Mountains are showing signs of acidification.

Southern pine forest growth rates are being impacted by ambient ozone levels. For seedlings, the annual growth reductions are between 2 and 5 percent. For mature pines, the annual growth reductions are between 0 and 10 percent. Ozone effects on mature southern yellow pines have resulted in decreased growth rates. Projected increases in ozone concentrations will likely have significant negative impacts on pine forests in the South.

Forest area and growth rates could increase across the South with moderate increases in air temperatures and carbon dioxide concentrations during the 21st century. Severe temperature increases could negatively affect forest productivity and area, especially if precipitation rates do not increase to compensate for increased water demands. Carbon storage in southern forest ecosystems, including public, private, and industrial forests , could make a significant sequestration contribution. Future policies, incentive programs, and forest management intensity will affect carbon sequestration rates. However, land use change, more than changes in climate or atmospheric chemistry, has been and probably will continue to be the most important determinant of carbon storage, uptake, and release in terrestrial ecosystems. Detailed spatial and temporal predictions of abiotic stressor effects on forest sustainability are not possible without long-term improvements in regional monitoring and studies designed to understand specific and integrated broad-scale stress responses at forest ecosystem, community, and species levels.

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10 Tables and Figures

Table 1--Acid Neutralizing Capacity (ANC) categories for brook trout response[a]

µeq/L	Classification	Biological response
> 50	"not acidic"	reproducing brook trout populations expectedwhere habitat is suitable
20 - 50	"transitional"	extremely sensitive to acidification; brook trout response variable
0 - 20	"episodically acidic"	sub-lethal and/or lethal effects on brook trout likely
< 0	"chronically acidic"	lethal effects on brook trout likely

[a] Source: Bulger and others 1998

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Table 2-- Estimates of ambient O_3 effects on growth of forest tree species occurring in the South[a]

Species	% Growth Reduction	Conditions	Source
Seedling/Sapling Studies			
Multiple species	0-10	Shoot growth	Chappelka and Samuelson 1998
Southern pines	2-5	Summary estimate of 19 field-chamber studies	Teskey 1996
Loblolly Pine	0-3	Mean response to 50-200 ppm-hr	Taylor 1994 (synthesis- whole tree biomass)
	1-10	Sensitive family response to 50-200 ppm-hr	
Hardwoods	13	Values derived from response	Reich and others
Conifers	3	surface at 20 ppm-hr	1988
Black Cherry	10-24		Hogsett and others 1997
Yellow Poplar	5-13	Values derived from O_3 exposure-	
Sugar Maple	0-9	response functions and model-	
Red Maple	0-1	simulated tree and stand	
Loblolly Pine	2-5	response[b]	
E. White Pine	4-8		
Virginia Pine	0-1		
Mature Tree Studies			
Loblolly Pine	2-9	Whole tree carbon model using branch chamber data (GA)	Dougherty and others 1992
	3	Mean response	
	0-13	Mean annual weekly responses to O_3 and interactions of O_3 and moisture stress, 5 years (TN)	McLaughlin and Downing 1996
	0-5	Annual O_3 effect - no water stress	
	0-30	Annual O_3 effect - moderate water stress	
Hardwoods	3-16	Regional simulation with canopy-stand model across moisture	Ollinger and others 1997

		gradients. Highest reductions occurred in areas with highest O_3 levels and on soils with high water holding capacity where drought stress was absent.	1997

[a] Source: McLaughlin and Percy 1999, with additions provided

[b] Percent reduction in annual net primary production

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Table 3--Aboveground tree carbon in southern forests by owner group[a]

Owner group	Aboveground carbon	
	million tons	tons/acre
National forest	343	29
Other public	283	27
Forest industry	708	19
Other private	3369	24

[a] Source: Heath and Smith, 2000b. Estimates based on 1997 FIA data and FORCARB results.

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Table 4--Aboveground tree carbon in southern forests by forest type group[a]

Forest type group	Aboveground carbon	
	million tons	tons/acre
Longleaf-shortleaf pine	179	14
Loblolly-shortleaf pine	932	19
Oak-pine	619	21
Oak-hickory	1964	26
Oak-gum-cypress	911	32
Elm-ash-cottonwood	61	27
Maple-beech-birch	37	32

[a] Source: Heath and Smith, 2000b. Estimates based on 1997 FIA data and FORCARB results.

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Table 5--Current and predicted southern forestland distribution (%) by ownership and forest type[a]

	Forest industry		Timber investment management org.		Non-industrial private forestlands	
Forest type	2000	2020	2000	2020	2000	2020
Planted pine	63	81	69	81	10	14
Natural pine	11	2	9	3	14	10
Oak pine	4	2	2	1	14	13
Upland hardwoods	6	1	3	1	40	35
Bottomland hardwoods	12	11	9	8	14	12
Not stocked	1	1	3	1	1	1
Reserved	3	2	5	5	7	15

[a] Source: Siry, J. 2000.

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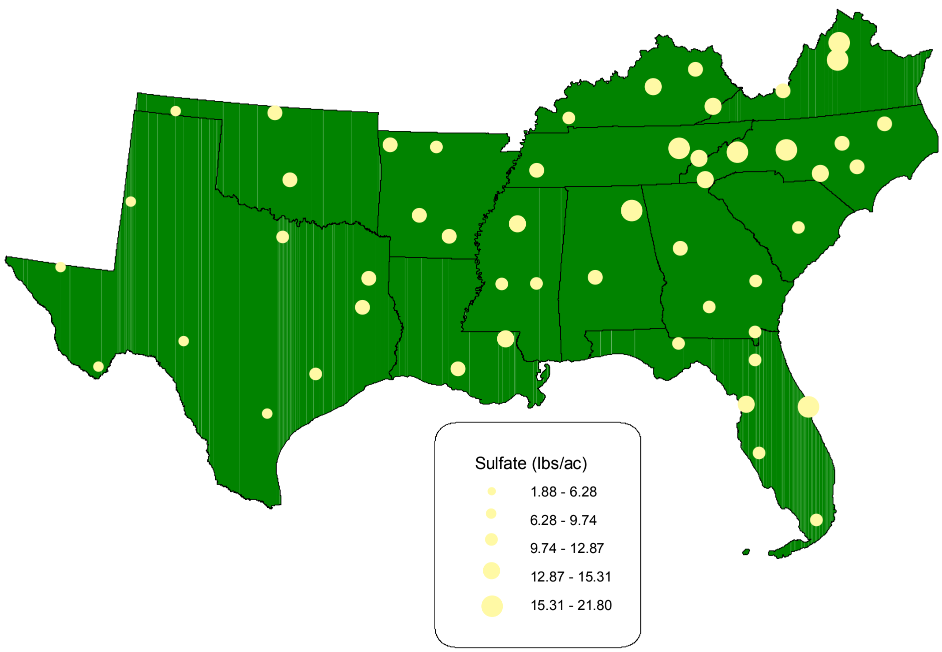
Figure 1--Current (1999) distribution of sulfate deposition in pounds per acre across the South.[a]



[a] Source: NADP 2000

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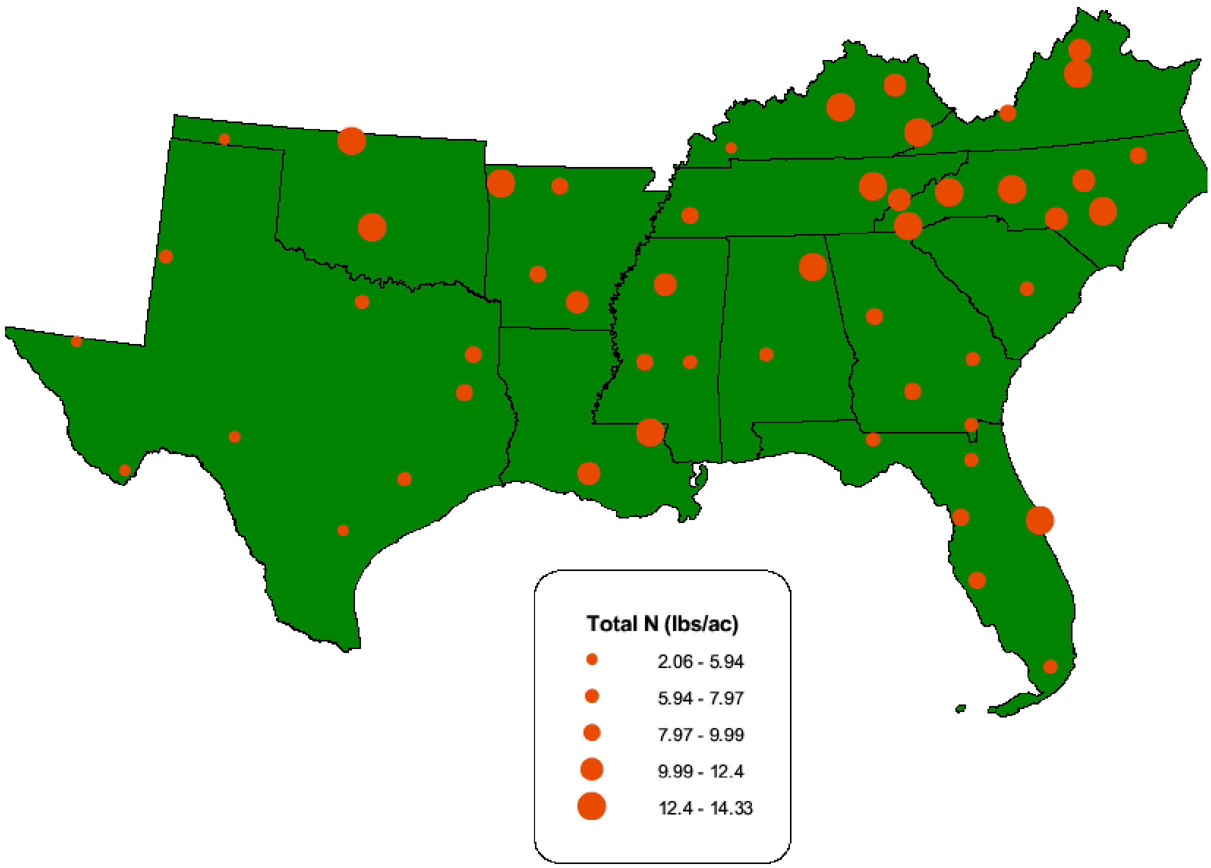
Figure 2--Current (1999) distribution of nitrogen deposition in pounds per acre across the South.[a]



[a] Source: NADP 2000

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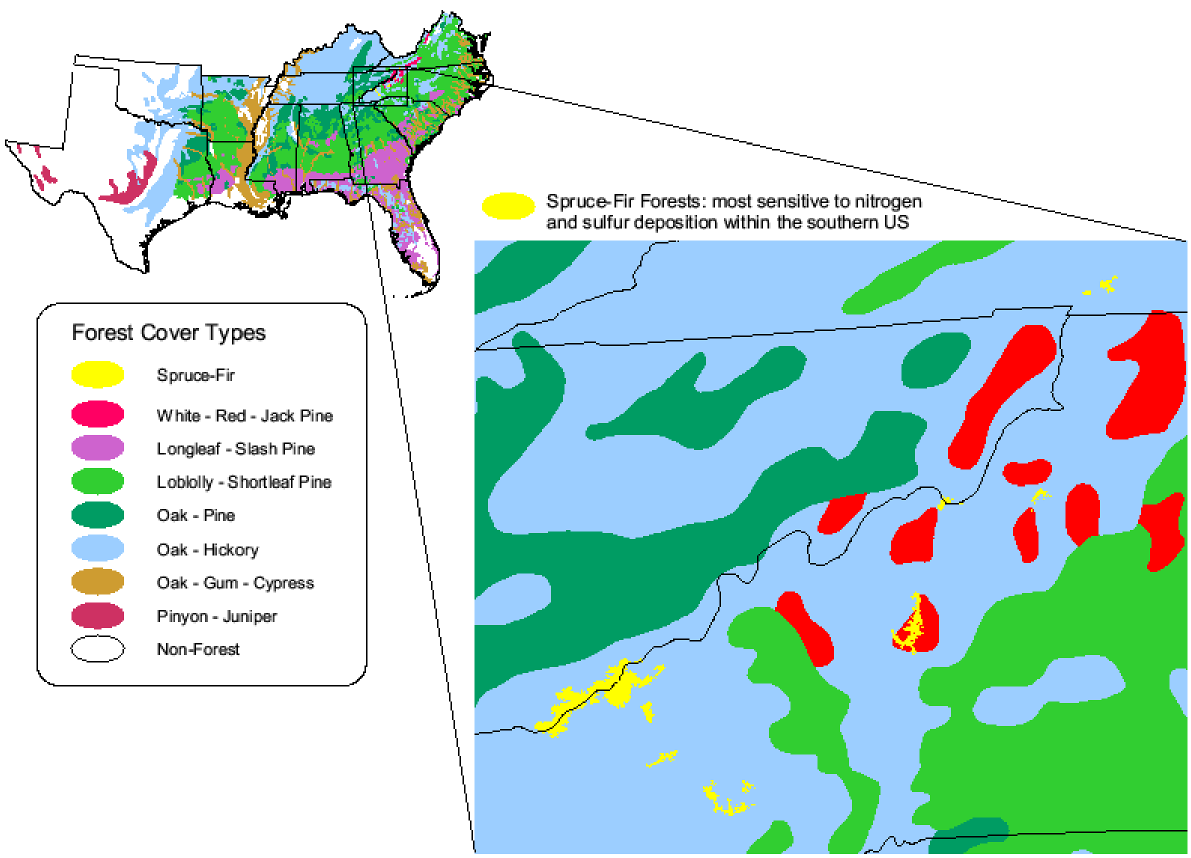
Figure 3--Distribution of spruce-fir and other southern forest types in eastern Tennessee, western North Carolina and southern Virginia.[a]



[a] Source: Eyre 1980

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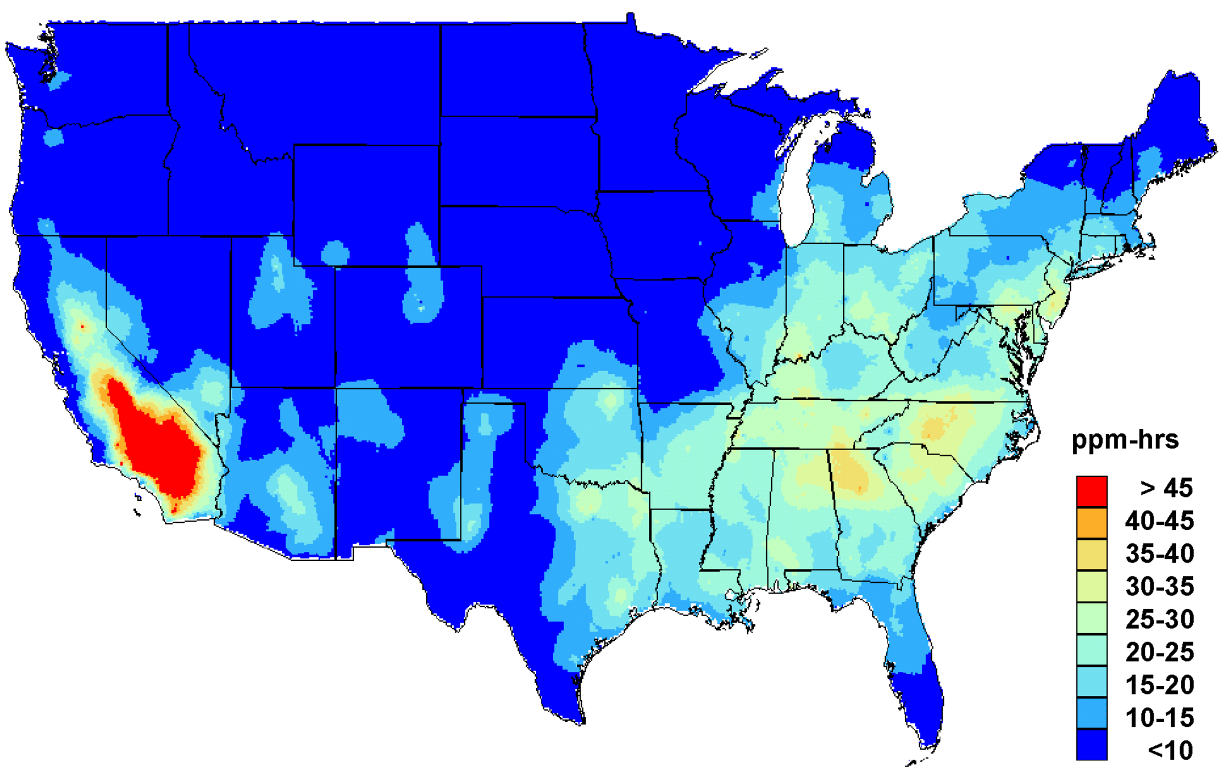
Figure 4--Three-month maximum daily SUM06 ozone exposure grid for 1990 showing spatial variability in ozone concentrations. The exposure grid was calculated by EPA using NHEERL-WED's Geographic Information System model to spatially interpolate SUM06 values calculated from the AIRS monitoring network.[a]



[a] Source: Schichtel and others 1996

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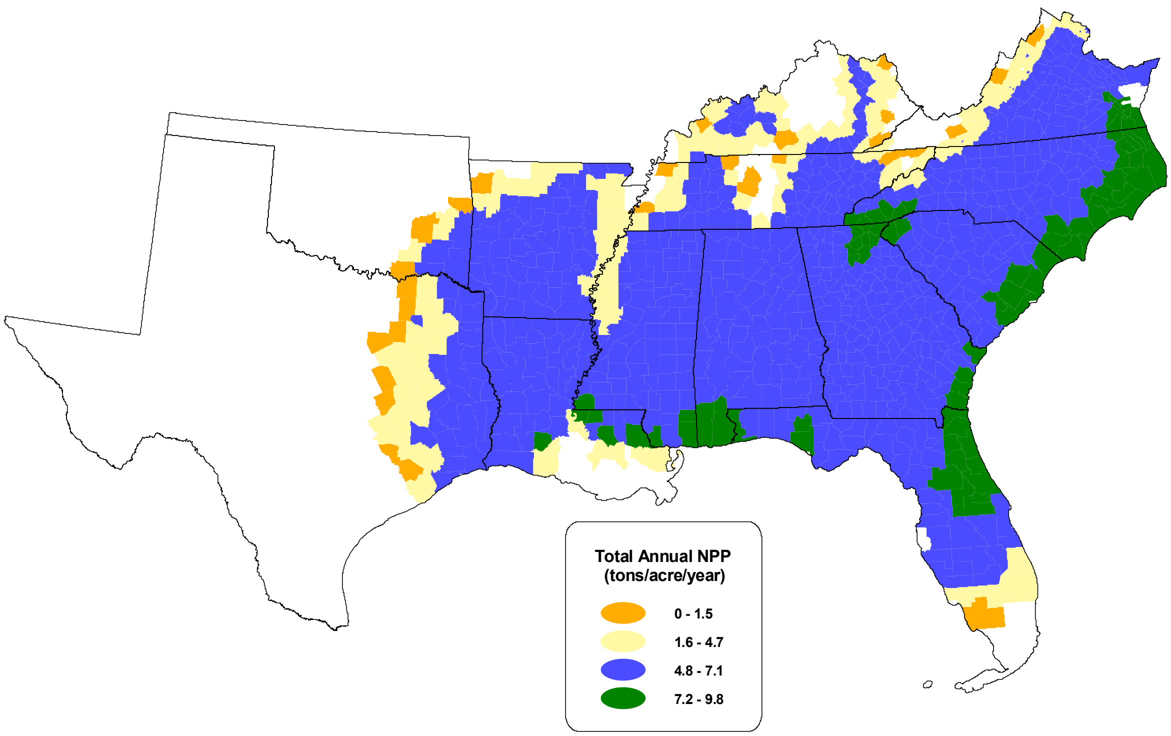
Figure 5--PnET-II model predictions of total potential annual southern forest growth, represented as net primary productivity (NPP) and averaged for the decade centered on 2000.[a]



Source: NAST 2001 (modified)

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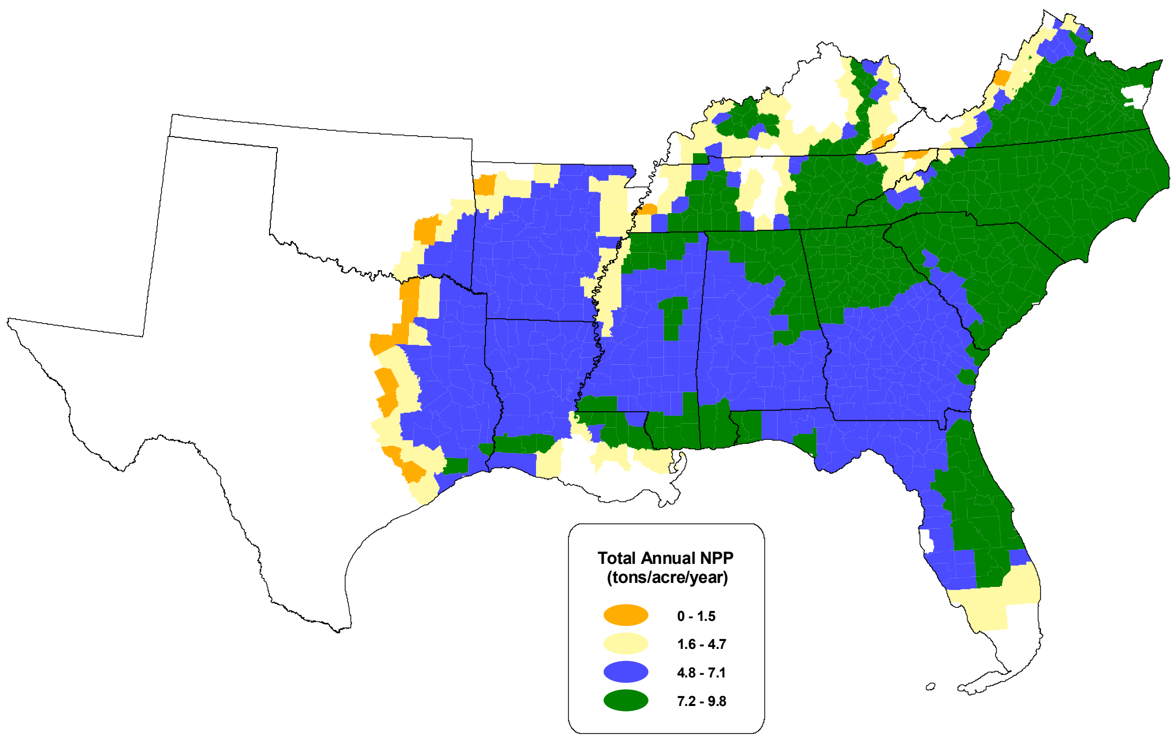
Figure 6--PnET-II model predictions of total potential annual southern forest growth, represented as net primary productivity (NPP) and averaged for the decade centered on 2040.



Source: NAST 2001 (modified)

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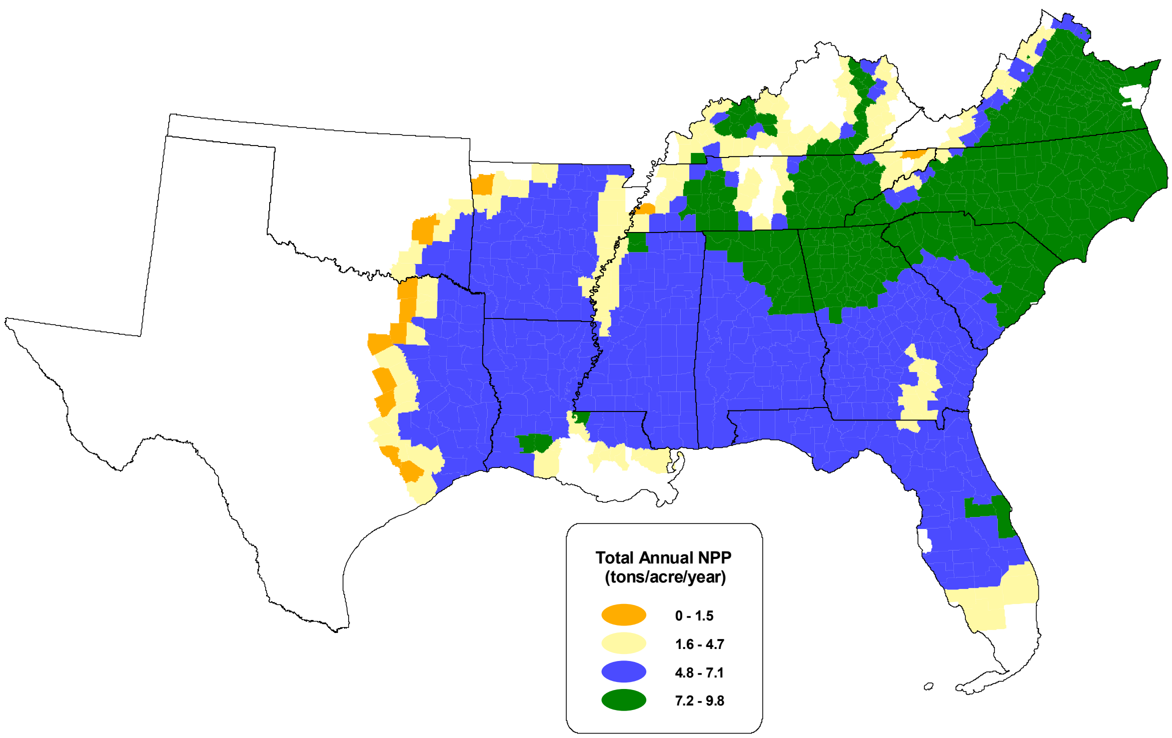
Figure 7--PnET-II model predictions of total potential annual southern forest growth, represented as net primary productivity (NPP) and averaged for the decade centered on 2090.[a]



[a] Source: NAST 2001 (modified)

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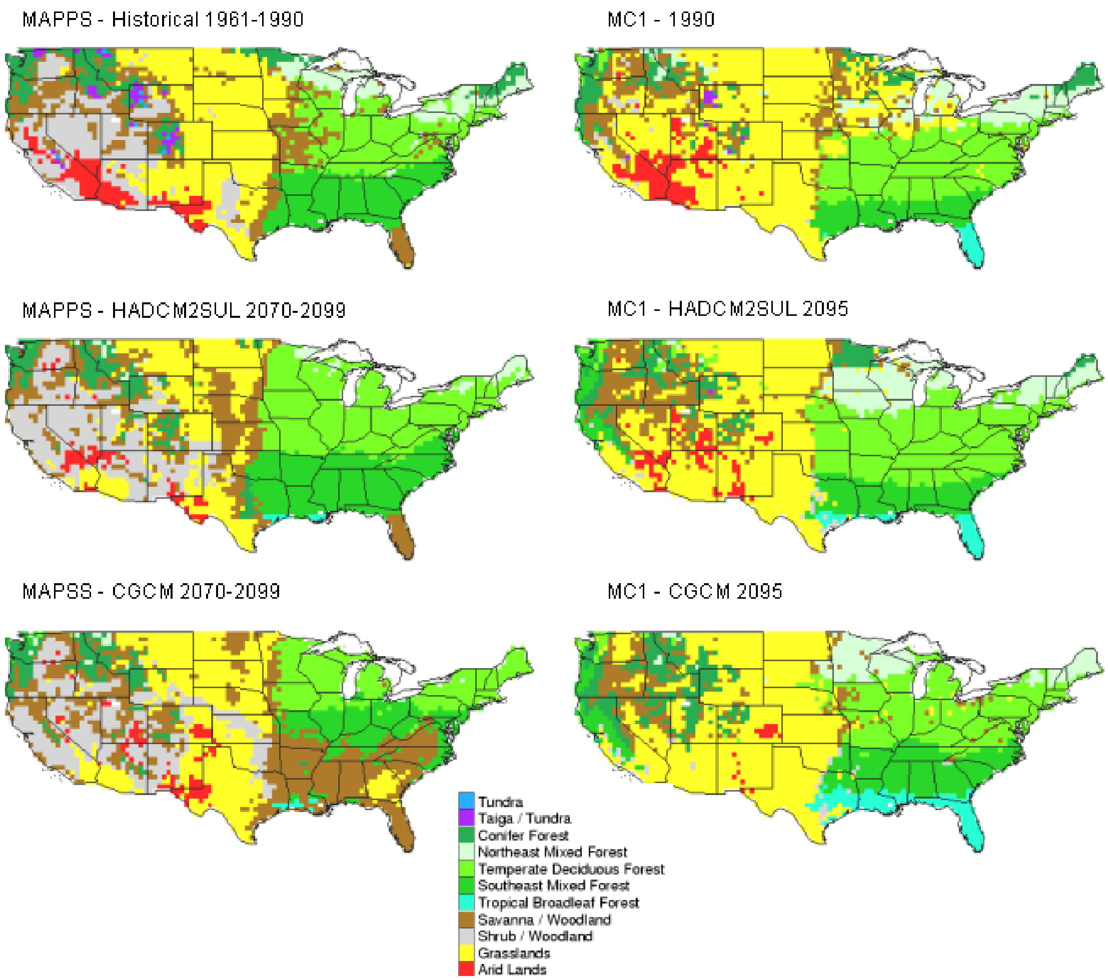
Figure 8--Current and future vegetation distribution as predicted by the biogeography models MC1 and MAPSS.[a]



[a] Source: Bachelet and others, in press

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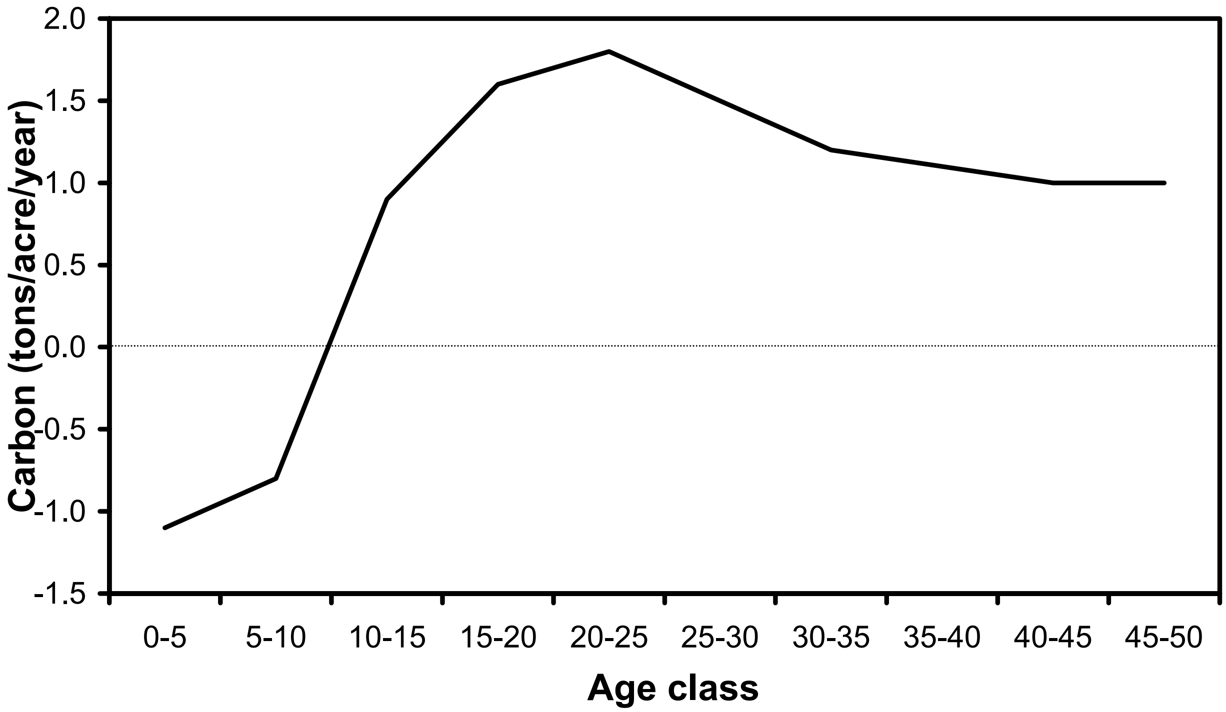
Figure 9--Average carbon uptake on land by age class of regeneration after harvest.[a]



[a] Source: Birdsey 1992

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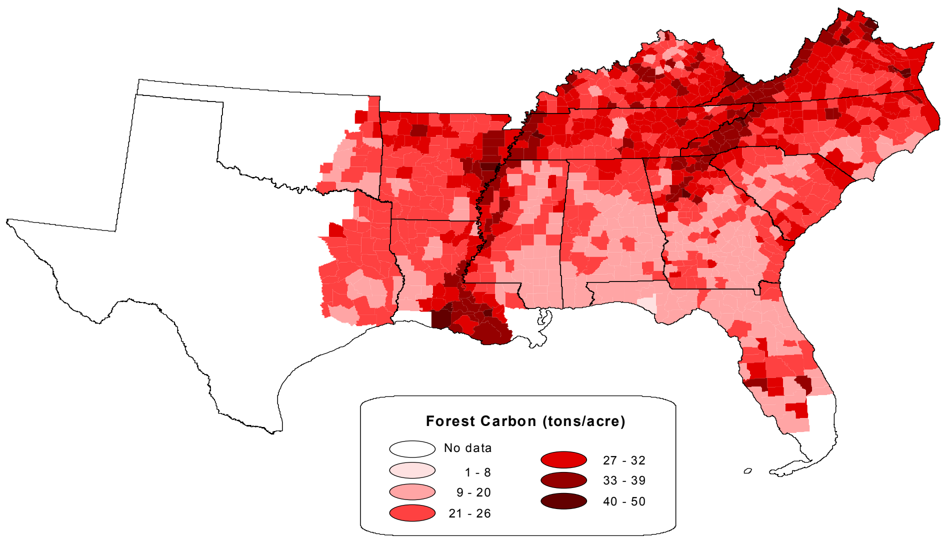
Figure 10--Total aboveground carbon per acre in southern forests.[ab]



[a] Source: Heath and Smith 2000b. Estimates based on 1997 FIA data and FORCARB results.

[b] Inventory begins in 1990, older products are not counted, and future predictions are cumulative amounts

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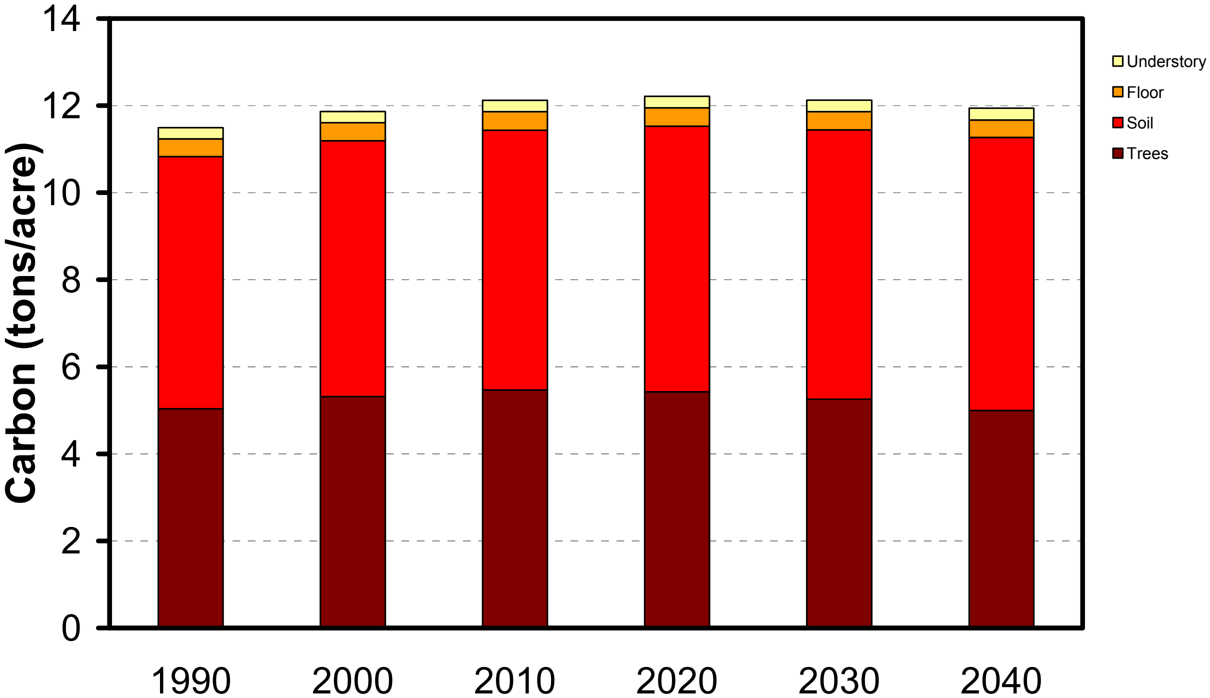
Figure 11--Current and future carbon inventory in southern forests by year.[ab]



[a] Source: Heath and Smith 2000b. Estimates based on 1997 FIA data and FORCARB results.

[b] Note that carbon in products is not included

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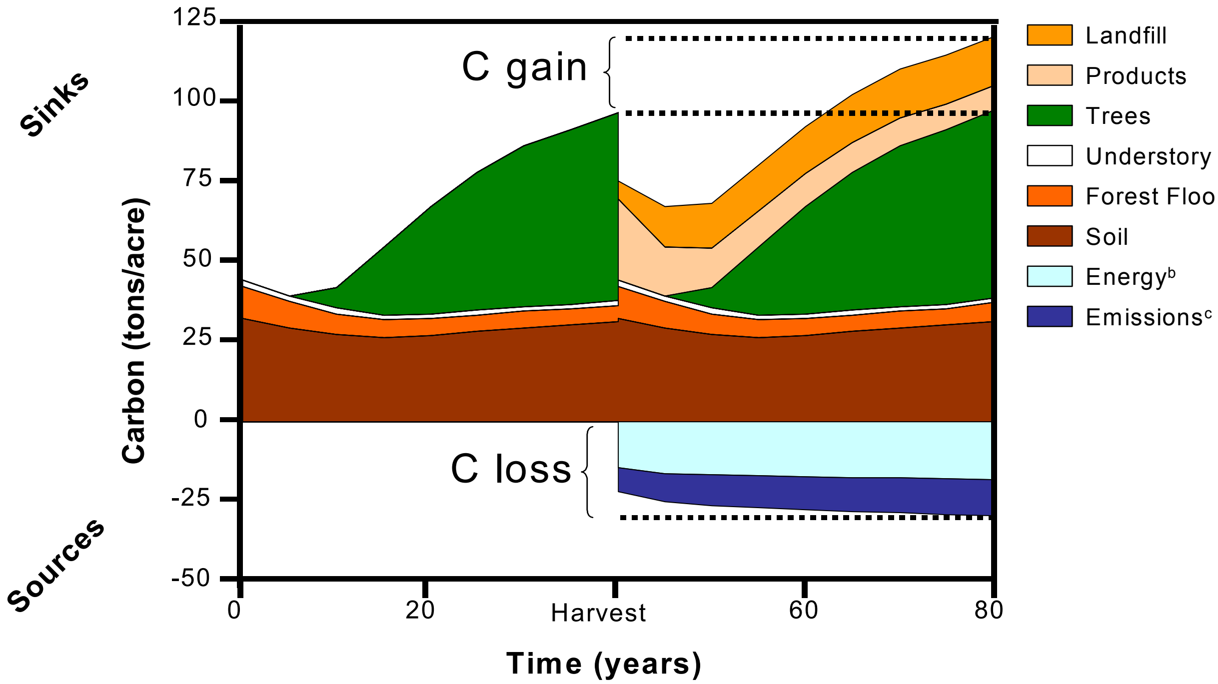
Figure 12--Estimated disposition of carbon on a highly productive southern site 40 years after harvest.[a]



[a] Source: Heath and Birdsey 2000

[b] Energy category represents wood burned for energy capture

[c] Emissions category represents wood burned without energy capture

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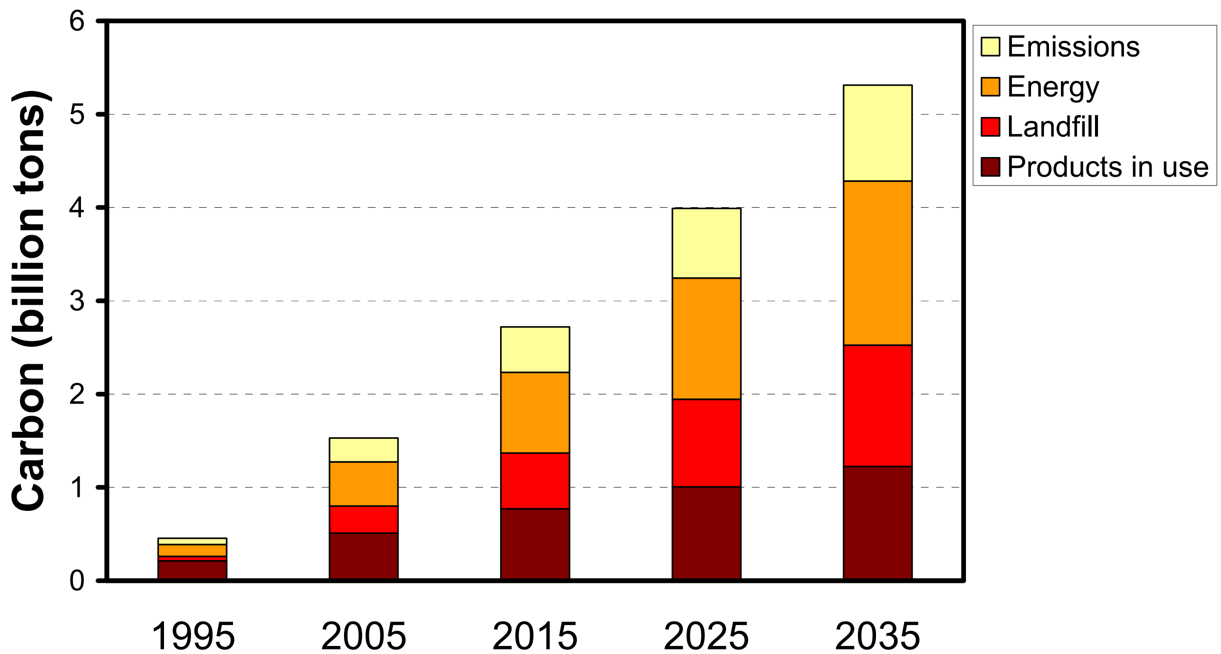
Figure 13—Fate of current and future carbon in wood removed from southern forests.[a b]



[a] Source: Heath and Smith 2000b. Estimates based on 1997 FIA data and FORCARB results.

[b] Inventory begins in 1990, older products are not counted, and future predictions are cumulative amounts

[c] Emissions category represents wood burned without energy capture

[d] Energy category represents wood burned for energy capture

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