




Southern Forest Science:
Past, Present, and Future

H. Michael Rauscher and Kurt Johnsen, Editors

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Chapter 33.

Forest Carbon Trends

in the Southern United States

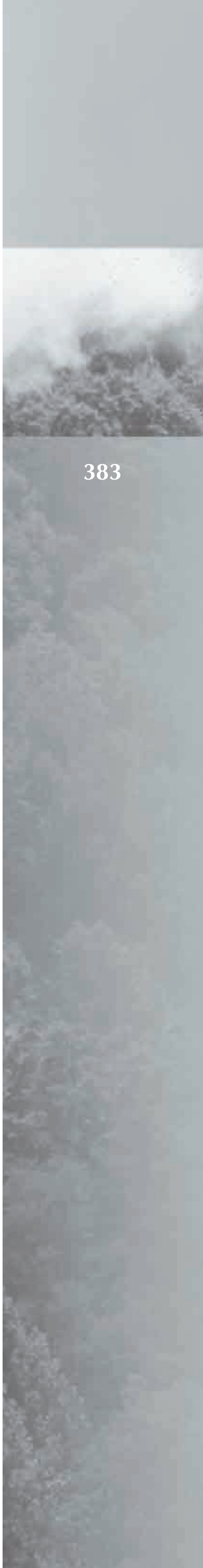
Robert A. Mickler, James E. Smith, and Linda S. Heath[1]

Abstract—*Forest, agricultural, rangeland, wetland, and urban landscapes have different rates of carbon (C) sequestration and total C sequestration potential under alternative management options. Future changes in the proportion and spatial distribution of land use could increase or decrease the capacity of areas to sequester C in terrestrial ecosystems. As the ecosystems within a landscape change as a result of natural or anthropogenic processes, they may go from being C sinks to being C sources or vice versa. We used periodic forest inventory data from the U.S. Department of Agriculture Forest Service's Forest Inventory and Analysis Program and Landsat Thematic Mapper data to obtain estimates of forest area and type. A simulation model for estimating and predicting C budgets (FORCARB) and a physiologically based forest productivity model (PnET) were used to generate estimates of historic, current, and future C storage for southeastern forests.*

INTRODUCTION

If the United States is to meet the challenge of future carbon dioxide (CO_2) emission and sequestration goals, the Southeastern region will play a critical role in increasing carbon (C) sequestration potential through conversion of nonforest land to forest land and through the management of forest lands. Terrestrial C fluxes caused by changes in land use and landcover must be quantified so that C sources and sinks in the United States can be identified. International treaties on greenhouse gas reduction require that current C emissions and sequestration potential of forest lands be determined so that baselines can be established for current and future forest C stocks. Changes due to afforestation (establishment of forest on land that is not now in forest use), deforestation (conversion of forest land to nonforest use), and reforestation (regeneration of forest after clearcut or significant partial-cut harvesting) are being used to derive estimates of forest C stocks for an historical baseline and future projections. Additional gains in C sequestration may be realized by increasing photosynthetic C fixation by plants, reducing decomposition of soil organic matter, reversing land use changes that contribute to global emissions, and creating energy offsets through the use of trees in urban environments.

The Southeastern United States can play an important role in a national program for reducing greenhouse gas emissions. The conversion of nonforest land to forest land results in an increase in aboveground and belowground sequestered C. The present-day conversion of abandoned farmlands to naturally regenerated forests and commercial forest plantations is contributing to an increase in the region's terrestrial C sink. In this chapter, we present historic, current, and future projections of forest C as simulated by an empirical simulation model used to estimate and predict C budgets (FORCARB) and a physiologically based forest productivity model (PnET).



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[1] Assistant Technical Director, Mantech Environmental Technology, Inc., Research Triangle Park, NC 27709; and Research Plant Physiologist and Research Forester, U.S. Department of Agriculture Forest Service, Northern Global Change Program, Durham, NH 03824, respectively.

MODELING HISTORIC AND CURRENT ESTIMATES OF FOREST CARBON

Ecosystem C pools for the aboveground portion of southern forest ecosystems were estimated using an inventory and modeling approach. Similar approaches have been employed by Plantinga and Birdsey (1993), Heath and Birdsey (1993), Birdsey and Heath (1995), Turner and others (1995), Intergovernmental Panel on Climate Change (1997), and Houghton and others (1999). Forest inventory data were obtained from the U.S. Department of Agriculture Forest Service (Forest Service), Forest Inventory and Analysis Program (FIA) (Miles and others 2001, Smith and others 2001). One can estimate regional C stocks by multiplying forest area by C per unit area. If a second survey is conducted at a later time, then the rate of change in the C stocks can be calculated as the change in C mass divided by the time between inventories in years. Traditional forest inventories provide the data required for calculating C mass. Approximately 50 percent of live tree biomass, or dry weight, is C.

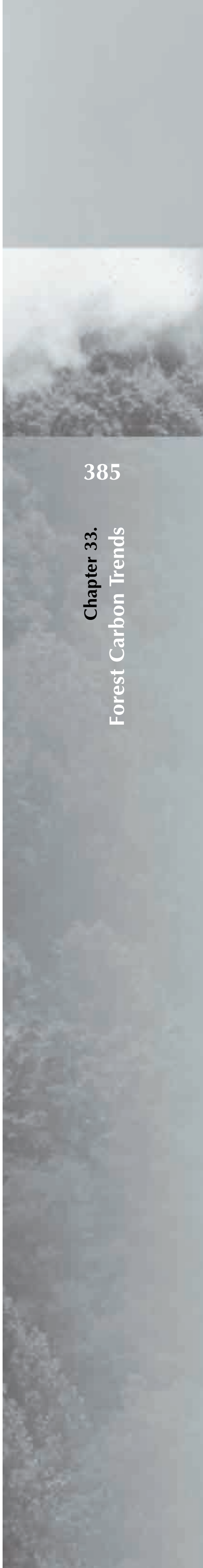
Since the early 1950s, forests in the United States have been surveyed periodically on a Statewide basis. The inventories have been conducted more intensively on the more productive forest land known as timberland. Timberland is defined as land capable of producing in excess of 20 cubic feet per acre per year of industrial wood products and not designated as reserved. Approximately 94 percent of southern forests are timberlands. Significant areas of less productive or reserved forest lands that have not been inventoried in the past exist in Texas, Oklahoma, and Florida. FIA surveys were designed for estimating forest area and merchantable timber volume. Tree volume can be converted to C mass by means of basic models or conversion factors. C in other forest components can be estimated similarly on the basis of forest attributes. Forest C is often assessed separately for a number of pools. For the purposes of this chapter, we partition the forest into five components: (1) aboveground live trees, (2) aboveground standing dead trees, (3) down dead wood (including stumps), (4) understory vegetation, and (5) the forest floor. We focus on aboveground pools in this chapter because of the uncertainty in belowground C estimates, and because there are accounting difficulties relating to the transfer of large blocks of soil C as a consequence of land use change (Heath and others 2003).

Another important aspect of forest C budgets in the United States is the fate of C in harvested wood. The categories used to describe harvested wood products in C budgets are (1) C in wood products in use, (2) C in landfills, (3) C emissions from wood burned to produce energy, and (4) C emissions from wood either decaying or burned without producing energy. Release of C emissions may result from burning of wood for energy at the mill, from other burning of fuel wood, or from burning of biofuels made from wood. The sum of the four categories of wood products is equal to the total amount of C harvested. Estimates of C in harvested wood products are based on national estimates from Skog and Nicholson (1998), partitioned by State on the basis of the ratio of statewide removals to national removals (Smith and others 2001).

Forest Carbon Estimates from Past Inventories

Forest inventory data are available for the last half of the 20th century. The data were compiled for years 1953, 1963, 1977, 1987, 1992, and 1997. The Forest Service has a detailed plot-level database for the forest inventory data compiled for the years 1987, 1992, and 1997. For the other years, only forest statistics aggregated across the landscape are available (Smith and others 2001).

Our estimates of historical tree C mass are based on (1) generalized tree biomass equations (Jenkins and others 2003); (2) tables of volume distributed among diameter classes and forest areas (Smith and others 2001) aggregated across the landscape; (3) effects of ownership and forest type on C content from the databases associated with the 1987 and 1997 U.S. forest statistics (Smith and others 2001, Waddell and others 1989); and (4) the equations of Smith and others (2003). C density of forest growing stock was estimated from average tree volumes, diameter distributions, and biomass equations. Estimates of C in nongrowing stock and standing dead trees were based on similar relationships and data in the detailed 1987 and 1997 databases. The other nonstanding-tree C pools were estimated based on relationships for live-tree C pools from the 1987 and 1997 data, and on forest floor equations in Smith and Heath (2002), and understory vegetation information in Birdsey (1992, 1996).



MODELING CURRENT AND FUTURE ESTIMATES OF FOREST CARBON

The physical and chemical environments of forest ecosystems are changing at rates unprecedented in recent geologic time. The Mauna Loa record shows a 16.9-percent increase in the mean annual concentration of atmospheric CO_2 from 315.98 parts per million by volume (ppmv) of dry air in 1959 to 369.40 ppmv in 2000. The 2.87-ppmv increase in CO_2 concentration in 1997–98 is the largest single yearly increase since the Mauna Loa record began in 1958 (http://cdiac.esd.ornl.gov/ndps/ndp001.html). If emissions continue to increase at this rate and there are no measures taken to slow the growth of CO_2 concentrations, a doubling of atmospheric CO_2 is possible by 2100 (Houghton and others 1996). In addition to elevated atmospheric CO_2, climate change resulting from the production or use of greenhouse gases and sulfate aerosols has increased over the last century. Air temperatures have increased on average by 1 °F across the United States during this period. In the Hadley model scenario, the Eastern United States has temperature increases of 3 to 5 °F by 2100, with larger increases for other regions (National Assessment Synthesis Team 2000). The physiological responses of southern forest ecosystems to elevated CO_2 and climate change have been the subject of hundreds of publications. A detailed review of the literature on this topic for southern forests is presented in Mickler and Fox (1997).

In this section, we present the responses of southeastern forest to elevated CO_2 and climate change. The objective of the research described here is to utilize remotely sensed forest cover data linked to a productivity model to determine, evaluate, project, and map forest productivity in the Southeastern United States from the present to 2100. We hope eventually to integrate existing climate, soil, and remotely sensed landcover data, and the Hadley2Sul climate scenario for the Southeastern United States as input to forest process models to predict, validate, and project forest growth and forest biomass. This section will describe methods for linking Landsat Thematic Mapper (TM) landcover information and a PnET to estimate and display forest productivity.

Remotely Sensed Forest Classification

Forest cover mapping using spaceborne sensors has been a goal of forest managers since the launch of Landsat-1 in 1972. The enhanced spatial, spectral, and radiometric resolution available with the launch of Landsat-4 and subsequent Landsat satellites has improved the application of the TM sensor for discerning forest cover classification at Anderson Level II and III classification precisions at a pixel spatial resolution of 30 m. One of the projects sponsored by the Multi-Resolution Land Characteristics (MRLC) Consortium was production of landcover data for the conterminous United States. Landcover was mapped using general landcover classes. For example, forest is classified as deciduous, evergreen, mixed, and woody wetlands. Landcover classification was based on MRLC's Landsat-5 TM satellite data archive and a host of ancillary sources.

The Landsat TM data used for this project were preprocessed following the procedures described by MRLC for the National Land Cover Data (NLCD) set. The NLCD-selected TM scenes consist of data acquired between 1990 and 1994. Image processing for the NLCD set is described by Vogelmann and others (1998, 2001). Spectral information from leaf-on and leaf-off datasets was used to derive the landcover classification products. First-order classification products were developed using predominantly the leaf-off mosaics as a baseline and refined with the spectral data from the other season and ancillary spatial information. Further refinements in the classification were made using decision trees and visual inspection. Landsat TM and ancillary data in the NLCD set were acquired for the 13 Southeastern States from MRLC (http://www.epa.gov/mrlc/nlcd.html). Individual State flat landcover files were imported into ERDAS IMAGINE®. Image data were projected to Albers projection, NAD83 datum, GRS1980 spheroid, and units of meters. Individual State images were used to produce one regional mosaic image. Forest area was displayed and summarized for three NLCD landcover classes: (1) deciduous forest (class 41), (2) evergreen forest (class 42), and (3) mixed forest (class 43). The deciduous forest class was supplemented with the woody wetland class (class 91) to create a reclassified deciduous forest class. The accuracy of the landcover classification has been described by Yang and others (2001).

Land Use Change

Forest land and agricultural land account for 90 percent of the South's total land use. Historically conversion of forest land to agricultural use, and vice versa, has been driven primarily by changes in economic conditions (Adams and others 1996). Smith and others (2001), who analyzed Forest Service FIA survey data, reported that total forest in the South decreased from 91 471 000 ha in 1953 to 86 646 000 ha in 1997, a 5.3-percent decline. Murray and others (2001), who examined Natural Resources Inventory survey data, determined that the forest area of the region declined by 687 981 ha, or 1.1 percent, between 1982 and 1997. They then assessed the future effects of global climate change on forest and agricultural rents. Climate projections using the Hadley base scenario with a 2 °F (1 °C) and 4 °F (2 °C) warming combined with a 20-percent reduction in precipitation were applied to a model of land allocation for the Southeastern U.S. forest area decline by ~4 000 000 ha [2 °F (1 °C) warming] and ~8 000 000 ha [4 °F (2 °C) warming] by 2040. Given the uncertainty associated with any projection of change in forest area under global climate scenarios and the historical trend for the last 50 years showing only a slight decrease in forest area in the region, the present study is based on the assumption that forest area will remain constant to 2100. We report the effects of climate change on the future productivity of the region's forests with the knowledge that changes in forest and agricultural returns may change forest area in the future.

Forest Productivity Modeling

We utilized the physiologically based, monthly time-step process model PnET to predict forest productivity and hydrology across a range of climates and site conditions. PnET predictions of forest productivity have been correlated with average annual growth in site basal area measured across the Eastern United States (Aber and Federer 1992), and predictions of forest biomass from PnET have been correlated with average annual growth in basal area measured at sites across the Southeastern United States (McNulty and others 1998). Forest biomass predictions for 2000, 2050, and 2100 were estimated using a decadal mean of net primary production (NPP) from the PnET model. Input data required by PnET include monthly climate parameters, soil water-holding capacity (WHC), and species- or forest-type specific vegetation parameters. PnET output is dependent on the spatial resolution of input data and includes forest growth, evapotranspiration, drainage, and soil water stress over time.

Monthly climate variables required by PnET include minimum and maximum air temperature, total precipitation, and solar radiation. The Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) provides these variables for the period 1895–1993 across the continental United States at a 0.5° by 0.5° resolution (Kittel and others 1997) (http://www.cgd.ucar.edu/vemap/datasets.html). VEMAP also provides transient climate scenarios that include the same monthly climate variables for 1994–2100, based on general circulation models developed at the Hadley Centre and the Canadian Climate Centre (http://www.met-office.gov.uk/research/hadleycentre/index.html). These climate scenarios, Had2CMSul and CGC1, include temperature and precipitation effects related to increasing atmospheric CO$_2$ and sulfate aerosols. These datasets have been used to compare time-dependent ecological responses of biogeochemical and coupled biogeochemical-biogeographical models to historical time series and projected scenarios of climate, atmospheric CO$_2$, and nitrogen deposition. This dataset has the finest spatial resolution available with this level of temporal and spatial consistency, and hence, other input data are modified to match the 0.5° by 0.5° resolution for the model.

Soil WHC is derived from the CONUS-Soil dataset, which was developed by the Pennsylvania State University Earth System Science Center. The State Soil Geographic Data Base (STATSGO) Program was developed by the U.S. Department of Agriculture, Natural Resources Conservation Service to store and distribute soil survey information for U.S. lands. STATSGO maps were compiled from more detailed soil survey maps and present soil associations at a scale (1:250,000) more appropriate for regional analysis. Soil WHC information derived from the CONUS-Soil dataset (Miller and White 1998) was adapted to the 0.5° by 0.5° grid by area-weighted averaging of the CONUS soil series WHC polygons.

PnET vegetation variables include foliar nitrogen concentration, light extinction coefficient, and other physiological coefficients or constants derived from field measurements and published literature (Aber and Federer 1992). Based on the climate, soil, and vegetation input data, PnET calculates the maximum amount of foliage or leaf area that can be supported. NPP equals total gross photosynthesis minus growth and maintenance respiration for leaves, wood, and roots. Respiration is calculated as a function of the current and previous month's minimum and maximum air temperatures. Changes in water availability and plant water demand place limitations on leaf area produced; as vapor pressure deficit and air temperature increase above optimal photosynthetic levels, total leaf area decreases. Reduced leaf area decreases total C fixation and alters ecosystem hydrology. Transpiration is calculated from a maximum potential transpiration modified by plant water demand that is a function of gross photosynthesis and water use efficiency. Interception loss is a function of total leaf area and total precipitation. Evapotranspiration is equal to transpiration and interception loss. Drainage is calculated as precipitation in excess of evapotranspiration and WHC. Maximum water storage capacity is equated to WHC to a depth of 100 cm. Monthly evapotranspiration is a function of leaf area, plant water demand, and climate; i.e., air temperature, vapor pressure deficit.

We report PnET predictions of NPP for evergreen, deciduous, and mixed forests. The PnET model runs were performed for evergreen and deciduous forest types. NPP for mixed forest types was assumed to be a 50:50 mix of deciduous and evergreen NPP. Estimates of NPP were output at the 0.5° by 0.5° resolution, and then Anderson Level II forest-cover type pixels were assigned NPP values within each 0.5° by 0.5° cell. The resulting estimates of forest productivity across the Southeastern United States are stored at a 30-m spatial resolution and include information about attributes for specific forest types. Forest biomass predictions for 2000, 2050, and 2100 were estimated using decadal means of NPP from the PnET model.

RESULTS AND DISCUSSION

Estimates of Carbon Stocks in Southern Forests

Southern forests presently contain 5810 Mt of aboveground C on 87 million ha. Forests of the conterminous United States contain 20 340 Mt of aboveground C on 250 million ha. Thus the South accounts for approximately 29 percent of aboveground forest C stock in the conterminous United States. Allocation of this stock among forest ecosystem pools is shown in table 33.1. The sum of standing C in live and dead trees is provided in table 33.2 by forest type and ownership. The majority of C is in privately owned forests and in hardwood forest types.

Countywide estimates of mean aboveground forest C density are shown in figure 33.1. Aboveground C includes that in live and dead trees, understory vegetation, down dead wood, and the forest floor. Values for each county represent the mean for forest land within the county. Only counties with at least 5 percent of area classified as forest are included. Mean net annual growth for the period 1987–97 is shown in figure 33.2. The C pool represented in this figure includes the aboveground portion of all live trees having diameter at breast height greater than 2.5 cm. Net annual growth is essentially the net annual change in live tree C stock, a definition consistent with the use of the term in summary forest statistics of the United States (Smith and others 2001).

Estimates of Forest Carbon Stocks 1953–97

In the Southern States, aboveground forest C stocks generally accumulated steadily between 1953 and 1997 (fig. 33.3). The mean annual change in tree C stocks between 1953 and 1997 (table 33.2, column 2) is calculated as the difference between C stocks in the 2 years divided by the interval in years (44 years). A positive value represents an average increase in C stock, as in the case of oak-hickory forests, while a negative value indicates an average decrease, as in the case of privately owned longleaf-slash pine forests. Because these are total C estimates, the differences could result from changes in the area of forest, or in C density, or both. Between 1953 and 1997, total area of

Table 33.1—Mean aboveground carbon density of productive southern forests (timberlands) by forest type and carbon pool, 1997

	Forest type		
Carbon pool	Softwood	Mixed	Hardwood
	Mg carbon/ha		
Live trees	37.7	55.4	56.0
Standing dead trees	1.7	3.0	3.1
Understory vegetation	2.9	2.2	2.9
Down dead wood	3.3	7.4	7.5
Forest floor	9.3	7.6	5.7

Table 33.2—Mean aboveground tree carbon mass of southern forests by forest type and ownership classifications, 1997[a]

Forest type	Mean annual carbon change 1953–97	Total tree carbon	Carbon density	Forest area
	Mt carbon per year	*Mt carbon*	*Mg carbon/ha*	*1 000 ha*
		Privately owned forests		
Miscellaneous conifer	0.1	14	74.1	193
Longleaf-slash pine	-1.8	148	33.2	4 468
Loblolly-shortleaf pine	0.8	721	39.4	18 286
Oak-pine	6.0	486	45.1	10 767
Oak-hickory	23.4	1 686	59.3	28 445
Oak-gum-cypress	6.4	734	70.8	10 356
Elm-ash-cottonwood	0.3	52	61.5	851
Maple-beech-birch	0.3	28	71.5	397
Other Eastern types (including nonstocked)	0.4	23	8.9	2 541
Total	35.8	3 892	51.0	76 303
		Publicly owned forests		
Miscellaneous conifer	0.1	6	66.7	86
Longleaf-slash pine	0.2	34	38.8	883
Loblolly-shortleaf pine	0.3	97	48.8	1 988
Oak-pine	1.1	75	52.9	1 418
Oak-hickory	3.8	229	71.6	3 198
Oak-gum-cypress	1.0	113	71.9	1 572
Elm-ash-cottonwood	0.1	8	74.9	102
Maple-beech-birch	0.1	6	83.7	72
Other Eastern types (including nonstocked)	< 0.1	6	5.8	1 025
Total	6.6	574	55.5	10 343
Total South	42.4	4 466	51.5	86 646

[a] The carbon pool includes aboveground portions of live and standing dead trees. Mean annual carbon change between 1953 and 1997 is calculated as the net change in carbon stock divided by the number of years.

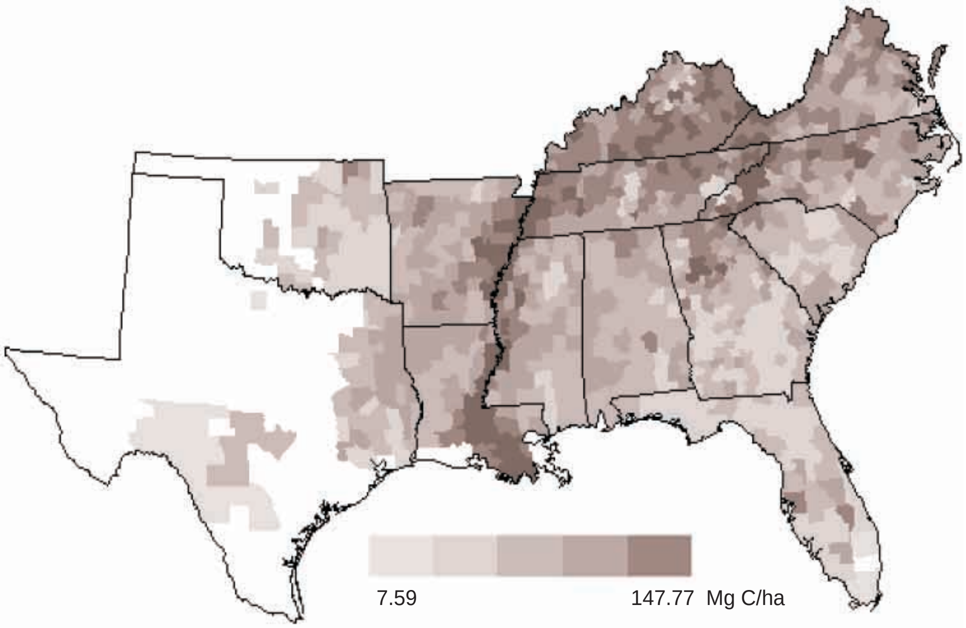


Figure 33.1—Aboveground carbon (C) density (Mg C/ha) for forested lands in 1997 in the Southern United States.

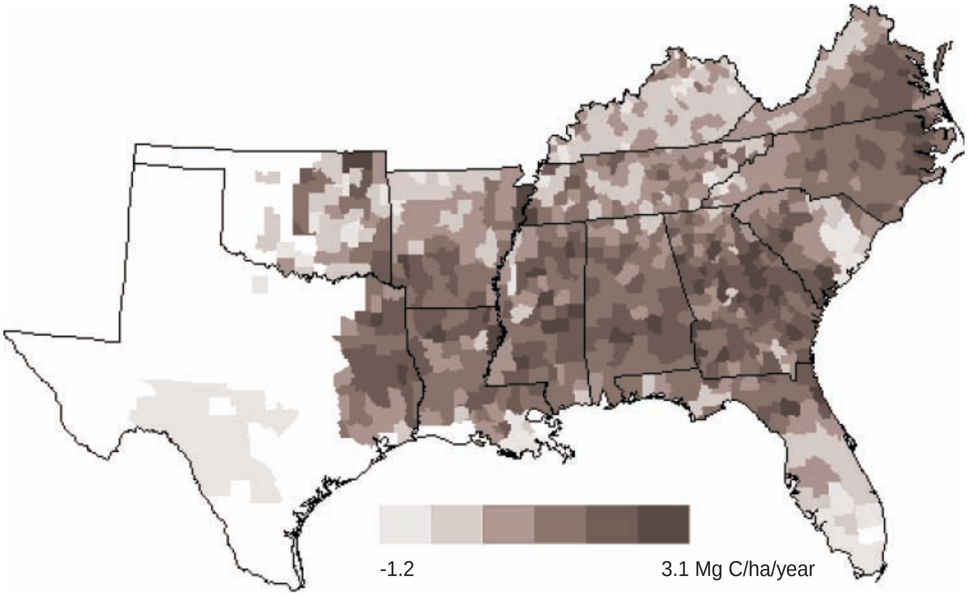


Figure 33.2—Mean net annual tree growth 1953–97 in terms of carbon (C) density (Mg C/ha/year) for forested lands in the Southern United States.

privately owned pine forest in the South decreased by 18 percent, but total C in trees decreased by only about 2 percent (see table 33.2). During this interval, the proportion of planted pine to all pines increased from about 2 percent to about 50 percent.

An estimate of the annual forest contribution of C for each Southern State is presented in figure 33.4. Estimates of C in harvested wood products are given in figure 33.5. All States have increased C in forests over the period. A number of States have sequestered 5 to 6 Mt C per year in forest ecosystems. Many States have also sequestered an additional 2 to 3 Mt C per year in products in use and landfills, with an additional amount of C in wood burned for energy.

Estimates of Forest Carbon Stocks 2000–2100

One can only speculate about the effects of global climate change and socioeconomic responses to the change on the future composition of forest ecosystems. The analysis reported here provides an estimate of potential forest production for 2000, 2050, and 2100 for the Southeastern United States. This analysis is based on an uncalibrated model of forest C balance, a warmer and wetter climate projected under the Hadley2Sul scenario, and forest cover from Landsat TM data (table 33.3). The trend in total forest C stocks between 2000 and 2050 was generally steady C accumulation throughout the period for States in the northern portion of the region and decreased C accumulation in

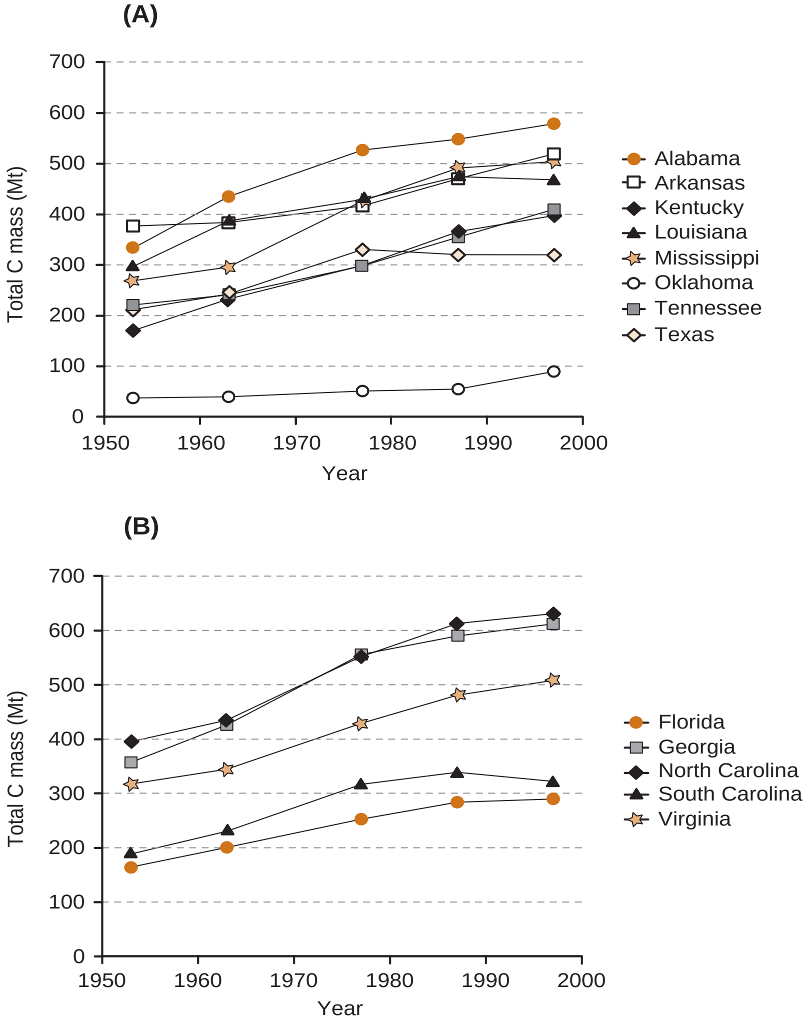


Figure 33.3—Estimated total aboveground forest carbon (C) stock for (A) Southcentral and (B) Southeastern States 1953–97. Total C mass (Mt) is for all productive forest land within each State. Aboveground C includes that in live and dead trees, understory vegetation, down dead wood, and the forest floor.

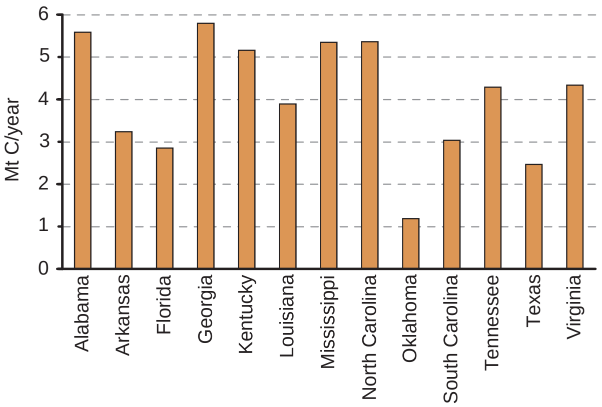


Figure 33.4—Estimated mean annual change in aboveground forest carbon stock 1953–97. Estimates are for productive forest land.

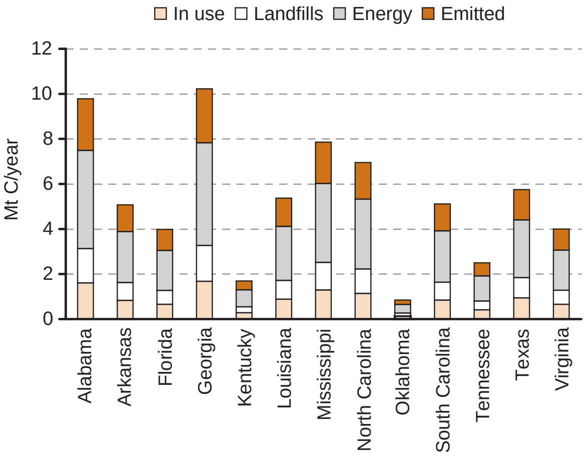


Figure 33.5—Estimated mean annual change of carbon in the harvested products categories 1953–97.

Table 33.3—Hadley 2000, 2050, and 2100 minimum, maximum, and average net primary production for all forest types

	Hadley 2000			Hadley 2050			Hadley 2100		
State	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
					g carbon/m²/year				
Alabama	1064.2	2320.7	1313.9	1080.6	2158.0	1338.3	674.5	1761.8	1197.4
Arkansas	885.6	1464.4	1151.0	822.9	1480.3	1117.4	744.5	1534.7	1158.1
Florida	1172.8	2320.7	1554.6	1020.9	2191.6	1430.5	391.2	1806.0	1088.4
Georgia	1049.9	2019.8	1298.1	1004.4	1954.7	1323.5	360.2	2026.3	1127.4
Kentucky	997.3	1544.2	1213.2	1017.9	1702.7	1344.8	1006.2	1633.1	1328.5
Louisiana	1037.5	2331.2	1506.9	893.3	2171.1	1363.1	805.8	1755.7	1225.4
Mississippi	1078.1	2086.4	1367.4	999.0	2013.9	1310.2	884.9	1629.6	1210.0
North Carolina	1078.5	2135.5	1424.4	1269.9	2280.3	1627.4	1152.8	2222.0	1488.3
Oklahoma	892.5	1357.3	1107.6	800.1	1224.7	1015.3	546.5	1390.4	1006.0
South Carolina	1060.3	1900.4	1339.2	1184.8	2174.0	1462.1	600.7	2222.0	1344.7
Tennessee	1034.3	1595.2	1286.7	1019.2	1899.3	1402.4	1013.0	1926.5	1371.9
Texas	871.6	2079.4	1202.0	721.9	1933.6	1055.1	597.9	1628.3	1015.1
Virginia	646.8	1936.4	1242.2	785.8	2173.1	1437.5	801.9	1910.3	1359.0
Regional	646.8	2331.2	1313.5	721.9	2280.3	1354.3	360.2	2222.0	1250.7

the Southern States (figs. 33.6A and 33.6B). There is a projected decreasing trend in total forest C stocks between 2050 and 2100 for all States in the region (figs. 33.6B and 33.6C). Future trends in climate suggest increasing air temperature that will affect woody tissue respiration, evapotranspiration, and the development of diurnal and seasonal water stress. Air temperature will likely be a contributing factor in lowering future forest productivity, especially along the Gulf Coastal Plains.

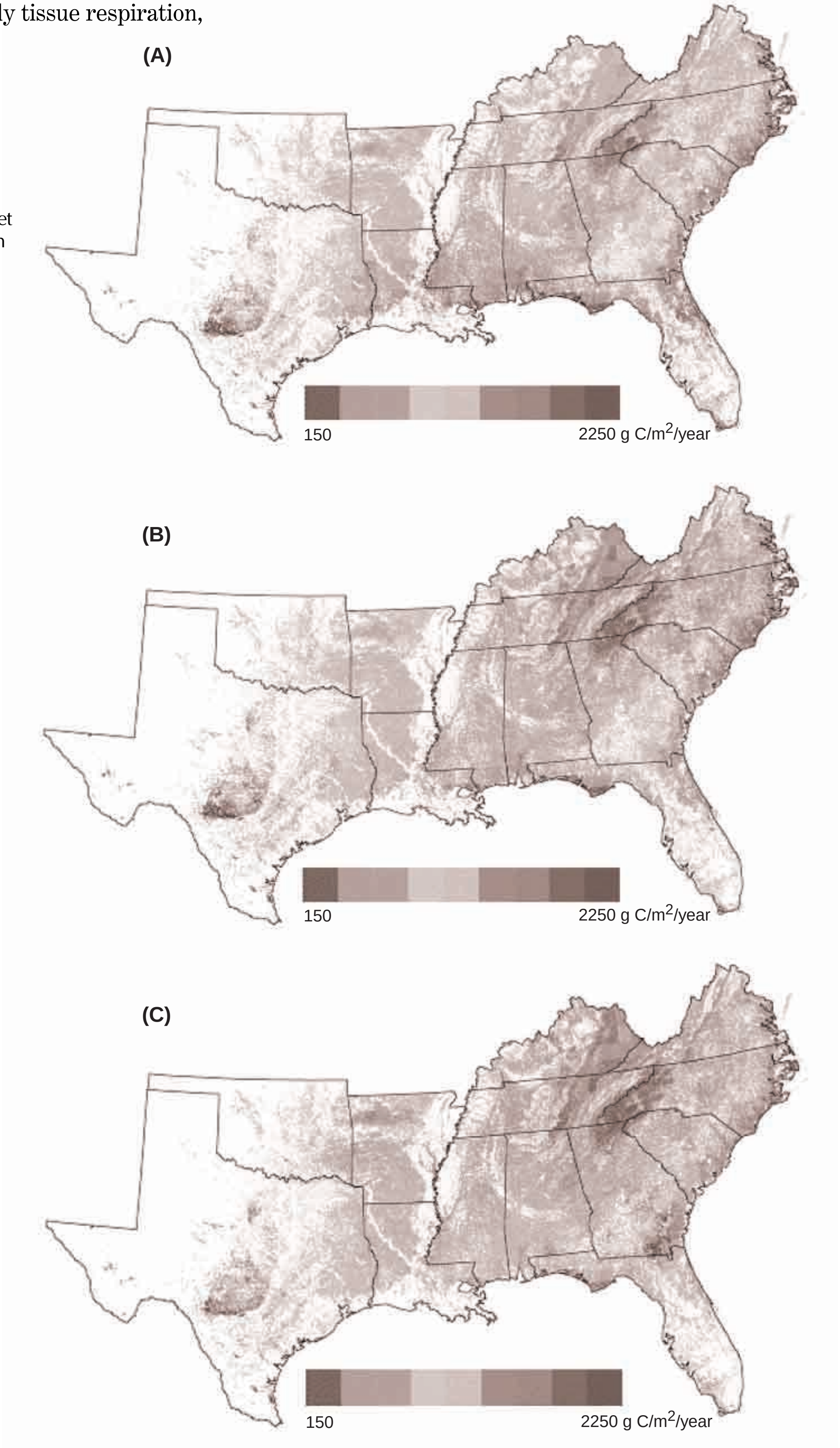


Figure 33. 6—Estimated annual net primary production [g carbon (C) m^2/year] for all forest types using the Hadley2Sul climate scenario for (A) 2000, (B) 2050, and (C) 2100.

ACKNOWLEDGMENTS

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Southern forests provide innumerable benefits. Forest scientists, managers, owners, and users have in common the desire to improve the condition of these forests and the ecosystems they support. A first step is to understand the contributions science has made and continues to make to the care and management of forests. This book represents a celebration of past accomplishments, summarizes the current state of knowledge, and creates a vision for the future of southern forestry research and management. Chapters are organized into seven sections: "Looking Back," "Productivity," "Forest Health," "Water and Soils," "Socioeconomic," "Biodiversity," and "Climate Change." Each section is preceded by a brief introductory chapter. Authors were encouraged to focus on the most important aspects of their topics; citations are included to guide readers to further information.

Keywords: Biodiversity, climate change, forest health, forest history, productivity, socioeconomics, soil, water.