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Modeling and Spatially Distributing Forest Net Primary Production at the Regional Scale

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ABSTRACT

Forest, agricultural, rangeland, wetland, and urban landscapes have different rates of carbon sequestration and total carbon sequestration potential under alternative management options. Changes in the proportion and spatial distribution of land use could enhance or degrade that area's ability to sequester carbon in terrestrial ecosystems. As the ecosystems within a landscape change due to natural or anthropogenic processes, they may go from being a carbon sink to a carbon source or vice versa. Satellite image analysis has been tested for timely and accurate measurement of spatially explicit land use change and is well suited for use in inventory and monitoring of terrestrial carbon. The coupling of Landsat Thematic Mapper (TM) data with a physiologically based forest productivity model (PnET-II) and historic climatic data provides an opportunity to enhance field plot-based forest inventory and monitoring methodologies. We use periodic forest inventory data from the U.S. Department of Agriculture (USDA) Forest Service's Forest Inventory and Analysis (FIA) Program to obtain estimates of forest area and type and to generate estimates of carbon storage for evergreen, deciduous, and mixed-forest classes. The area information is used in an accuracy assessment of remotely sensed forest cover at the regional scale. The map display of modeled net primary production (NPP) shows a range of forest carbon storage potentials and their spatial relationship to other landscape features across the southern United States. This methodology addresses the potential for measuring and projecting forest carbon sequestration in the terrestrial biosphere of the southern United States.

IMPLICATIONS

Efforts to quantify live and dead forest biomass at the local and regional scale have been hindered by the uncertainty surrounding the measurement and modeling of forest ecosystem processes and fluxes. The interaction of elevated atmospheric CO_2 with climate, soil nutrients, and other forest management factors that affect forest growth and fuel loading will play a major role in determining future forest stand growth and the distribution of species across the southern United States.

INTRODUCTION

If the United States is to meet the challenge of future CO_2 emission and sequestration goals, the southern United States will play a critical role in increasing carbon sequestration potential through conversion of non-forestland to forestland and through the management of forestlands. Quantifying terrestrial carbon fluxes due to land use and land cover change is essential in identifying carbon sources and sinks in the terrestrial biosphere of the United States. Within the context of international treaties on greenhouse gas reduction, data on current carbon emissions and the sequestration potential of forestlands will be needed to establish a baseline of current carbon stocks and to estimate future forest carbon 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 the three forest-related land-use activities being used to derive estimates of forest carbon stocks for a historical baseline and future projections. Additional gains in carbon sequestration may be realized by increasing photosynthetic carbon 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 for fuels and the direct reduction in cooling energy use of buildings in urban environments.

The southern United States has an important role in meeting net reductions in greenhouse gas emissions for the nation. The conversion of non-forestland to forestland results in an increase in above- and below-ground sequestered carbon. Before European settlement, the southern U.S. landscape was primarily forests, grasslands, and wetlands. Most of the native forests were harvested and converted to agricultural lands and managed forests by 1920. The present-day conversion of abandoned farmlands to naturally regenerated forests and commercial forest plantations contributes to the increase in the region's terrestrial carbon sink. Southern forest ecosystems currently store 12,630 million tons of carbon sink.[1]

Carbon sequestered in southeastern forests is a source of fuel for prescribed and wildland forest fires. Fire is one of the dominant disturbances in U.S. forests and is a primary process that influences the vegetation composition and structure of any given location and helps shape the landscape mosaic. Forest structure and composition are influenced by fire regime. Areas burned by prescribed and wildland forest fires in North America can exceed 74 million acres per year. Fuel loads tend to vary between 3 and 500 tons per acre, with fuel consumption efficiency varying from 20 to 80%. If the projected changes in climate are realized during this century, an altered fire regime could have the most immediate and significant impact on forest ecosystems. Recent studies on the interaction of climate change and forest fires suggest that projected increases in atmospheric CO_2, air temperature, and variability in precipitation will increase seasonal fire severity ratings by 10–50% over most of North America. The area burned in the United States from wildland fire is projected to increase by 25–50% by the middle of the 21st century, with most of the increases occurring in Alaska and the southeastern United States.[2] Any attempt to measure and project forest carbon sequestration in the terrestrial biosphere of the United States must consider the increased risk of wildland fire from increased forest carbon sequestration and the role of forest fire as a source of carbon emissions.

Table 1. FIA estimates of total land, forest, and timberland areas (acres) in the southeastern United States, 1992.

Region, Subregion, and State	Total Land Area	Total Forestland[a]	Total Timberland[b]
South			
Southeast:			
Florida	34,558,000	16,549,000	14,983,000
Georgia	37,068,000	24,137,000	23,631,000
North Carolina	31,180,000	19,278,000	18,710,000
South Carolina	19,271,000	12,257,000	12,179,000
Virginia	25,343,000	15,858,000	15,292,000
Total:	147,419,000	88,078,000	84,794,000
South Central:			
Alabama	32,480,000	21,974,000	21,941,000
Arkansas	33,328,000	17,864,000	17,423,000
Kentucky	25,429,000	12,714,000	12,360,000
Louisiana	27,882,000	13,864,000	13,855,000
Mississippi	30,025,000	17,000,000	16,991,000
Oklahoma	43,954,000	7,539,000	6,122,000
Tennessee	26,380,000	13,612,000	13,275,000
Texas	167,625,000	19,193,000	12,548,000
Total:	387,104,000	123,760,000	114,515,000
South Total:	534,523,000	211,838,000	199,309,000
U.S. Total	2,263,259,000	736,681,000	489,555,000

[a]Land at least 10% stocked by forest trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated; [b]Forestland that is producing or is capable of producing 20 ft^3/acre/year of industrial wood and not reserved from timber harvest.

Accurate information on land cover types, spatial distribution, rates of change of forest characteristics, and forest inventory is required to estimate the carbon emission and sequestration potential of forestry-related land use activities and to assess the contribution of fuel wood to wildland fire risks. Remote sensing data, field plot-based forest inventory data, and forest modeling results and outputs provide an opportunity to optimize the connection between remotely sensed data and key forest growth and physiological parameters, soils, and climate in modeling spatiotemporal estimates of net primary production (NPP) across the region. The purpose of this paper is to introduce methodologies for linking remotely sensed Landsat Thematic Mapper (TM)-derived land cover, Forest Inventory and Analysis (FIA) data, and a forest ecosystem model (PnET-II) to estimate and spatially display forest productivity with Anderson Level II precision[3] for the southeastern United States.

EXPERIMENTAL METHODS

Study Region

The study region encompasses 534,523,000 acres in 13 states from the Atlantic coast west to Texas and Oklahoma. The region represents ~24% of the U.S. land area, 29% of the forestland, and 25% of the agricultural land. In 1992, forestland (land at least 10% stocked by forest trees of any size) covered 211,838,000 acres, or ~40% of the total land area in the region.[4] Southern forests remain a vital resource for the region and the nation, encompassing 41% of the timberland (forestland producing or capable of producing crops of industrial wood and not withdrawn from production) of the entire United States (Table 1).

The southern United States is divided into 10 geomorphic regions encompassing a diversity of climates, soil characteristics, and topography.[5] This diversity results in a corresponding diversity of tree species and forest types, including southern yellow pines, mixed pine–hardwoods, upland and bottomland hardwoods, and tropical hardwoods in Florida. Across much of the region, pine stands represent a transitional stage in natural succession to hardwood forest types. Mixed pine–hardwood stands are typically composed of 50% or more oak and other hardwoods and 25–50% pine.

Most of the timberland in the South is in nonindustrial private and forestry industry ownership. In 1992, private citizens, farmers, and the forest industry owned 90% of southern timberland. Nonindustrial private ownership includes large numbers of small parcels and a smaller number of large tracts. This ownership class is found most often near urbanizing areas, dispersed among cultivated lands, and in remote areas. Changing ownership and differing management objectives affect land cover and land use within the region.

Forest Inventory Data

The primary sources of estimates of forestland area, growth, and harvest are remote sensing and ground plot inventory data reported by the FIA program of the U.S. Department of Agriculture (USDA) Forest Service Southern Research Station.[4] Beginning in 1933, forested plots have been revisited during a 5- to 10-year state survey cycle. Before 1997, two states were inventoried concurrently and required two years each to complete the field surveys. During each inventory, FIA collects and then reports the status and trends in forest area and location; in the species, size, and health of trees; in total tree growth, mortality, and removals by harvest; in wood production and utilization rates by various products; and in forestland ownership. Recent enhancements to the FIA program include an annual partial sampling of field plots and additional information relating to tree crown condition, soils, complete vegetative diversity, and coarse woody debris.

The FIA program consists of a national core program that can be enhanced at the regional, state, or local level to address special interests. The national core consists of three phases. Phase 1 is a remote-sensing phase aimed at stratifying the land as forest or non-forest. This phase has historically been conducted using aerial photography but is now changing to a system based on satellite imagery. Phase 2 consists of a set of field sample locations composed of four subplots, each 1/24th of an acre and distributed across an area of one acre. FIA field locations are distributed across the landscape with approximately one sample location every 5935 acres. During this phase, field crews visit forested plots to confirm Phase 1 classification and estimate tree- and stand-level attributes. FIA estimates county-level forest area based on a double sampling estimate that uses either photo points or classified pixels and ground plots.[6] Phase 3 consists of a subset of the Phase 2 plots that are visited during the growing season to collect an extended suite of ecological data including full vegetation inventory, tree and crown condition, soil data, and coarse woody debris.

FIA data for the most recent field surveys (spanning 1988–1995) for the 13 southeastern states were obtained from the Forest Service FIA Eastwide Data Base (http://srsfia.usfs.msstate.edu/scripts/ew.htm). This database was developed to provide users with FIA field plot data in a manner consistent among states. Forest type groups and forest type names are grouped into three forest classes (evergreen, mixed, and deciduous) that correspond to Anderson Level II forest classes for each state (Table 2). The areas for each forest class are summarized and totaled for each state (Table 3).

Remotely Sensed Forest Classification

Forest-cover mapping using spaceborne sensors has been a goal of forest managers since the launch of Landsat-1 in

Table 2. Landsat landcover classes and FIA forest type groups and names.

Evergreen	Mixed	Deciduous
White-Red-Jack Pine	Oak-Pine	Oak-Hickory
White Pine	White Pine-Northern Red Oak- White Ash	Post Oak-Black Oak-Bear Oak
White Pine-Hemlock	Eastern Red Cedar-Hardwood	Chestnut Oak
Hemlock	Longleaf Pine-Scrub Oak	White Oak-Red Oak-Hickory
Spruce-Fir	Shortleaf Pine-Oak	White Oak
Balsam Fir	Virginia Pine-Southern Red Oak	Northern Red Oak
Red Spruce-Balsam Fir	Loblolly Pine-Hardwood	Yellow Poplar-White Oak-Northern Red Oak
Longleaf Pine	Slash Pine-Hardwood	Southern Scrub Oak
Slash Pine	Other Oak-Pine	Sweetgum-Yellow Poplar
Loblolly-Shortleaf Pine		Mixed Central Hardwoods
Loblolly Pine		Oak-Gum-Cypress
Shortleaf Pine		Swamp Chestnut Oak-Cherrybark Oak
Virginia Pine		Sweetgum-Nuttall Oak-Willow Oak
Sand Pine		Sugarberry-American Elm-Green Ash
Eastern Red Cedar		Overcup Oak-Water Hickory
Pond Pine		Atlantic White Cedar
Spruce Pine		Bald Cypress-Water Tupelo
Pitch Pine		Sweetbay-Swamp Tupelo-Red Maple
Table-Mountain Pine		Palm-Mangrove-Other Tropical
		Elm-Ash-Cottonwood
		River Birch-Sycamore
		Cottonwood
		Willow
		Sycamore-Pecan-American Elm
		Maple-Beech-Birch
		Sugar Maple-Beech-Yellow Birch
		Non-Stocked

Table 3. Comparison of FIA and Landsat TM forest area estimates of evergreen, deciduous, and mixed land cover (acres).

State		Evergreen	Deciduous	Mixed	Total Forestland
Alabama	FIA	7,447,109	9,918,991	4,521,745	21,887,845
	TM	6,565,100	9,802,600	8,016,200	24,383,900
	% Difference	13.43%	1.19%	–43.59%	–10.24%
Arkansas	FIA	5,135,027	10,399,709	3,211,736	18,746,472
	TM	4,691,100	11,035,900	3,966,000	19,693,000
	% Difference	9.46%	–5.76%	–19.02%	–4.81%
Florida	FIA	7,675,677	6,016,218	1,531,299	15,223,194
	TM	7,273,300	8,318,400	903,900	16,495,600
	% Difference	5.53%	–27.68%	69.41%	–7.71%
Georgia	FIA	11,277,955	10,075,426	3,810,015	25,163,396
	TM	8,919,100	11,315,300	4,486,200	24,720,600
	% Difference	26.45%	–10.96%	–15.07%	1.79%
Kentucky	FIA	709,445	10,927,311	889,457	12,526,213
	TM	741,500	13,102,979	1,851,000	15,695,479
	% Difference	–4.32%	–16.60%	–51.95%	–20.19%
Louisiana	FIA	5,006,652	6,819,761	1,886,597	13,713,010
	TM	4,725,500	5,716,000	2,863,700	13,305,200
	% Difference	5.95%	19.31%	–34.12%	3.07%
Mississippi	FIA	5,751,036	9,545,806	3,224,855	18,521,697
	TM	5,943,900	8,499,700	4,220,300	18,663,900
	% Difference	–3.24%	12.31%	–23.59%	–0.76%
North Carolina	FIA	6,450,720	10,106,875	2,622,686	19,180,281
	TM	6,074,000	11,964,700	3,643,000	21,681,700
	% Difference	6.20%	–15.53%	–28.01%	–11.54%
Oklahoma	FIA	1,119,019	3,571,699	720,687	5,411,405
	TM	926,100	7,604,700	1,099,300	9,630,100
	% Difference	20.83%	–53.03%	–34.44%	–43.81%
South Carolina	FIA	5,676,232	5,159,779	1,937,983	12,773,994
	TM	5,190,500	5,698,100	2,228,900	13,117,500
	% Difference	9.36%	–9.45%	–13.05%	–2.62%
Tennessee	FIA	1,397,767	10,270,222	1,591,537	13,259,526
	TM	2,013,300	11,901,400	3,149,900	17,064,600
	% Difference	–30.57%	–13.71%	–49.47%	–22.30%
Texas	FIA	4,337,903	5,017,972	2,539,329	11,895,204
	TM	9,615,100	2,866,100	4,605,000	17,086,200
	% Difference	–54.88%	75.08%	–44.86%	–30.38%
Virginia	FIA	3,449,495	10,366,170	1,964,702	15,780,367
	TM	2,097,700	11,036,000	3,807,300	16,941,000
	% Difference	64.44%	–6.07%	–48.40%	–6.85%
Southeastern United States	FIA	65,434,037	108,195,939	30,452,628	204,082,604
	TM	64,776,200	118,861,879	44,840,700	228,478,779
	% Difference	1.02%	–8.97%	–32.09%	–10.68%

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 98 ft^2. One of the projects sponsored by the Multiresolution Land Characteristics (MRLC) Consortium is the production of land-cover data for the conterminous United States.[7] Land cover is mapped using general land-cover classes. For example, forest is classified as deciduous, evergreen, or mixed. Land-cover classification is 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 (http://edc.usgs.gov/glis/hyper/guide/mrlc#mrlc4) for the

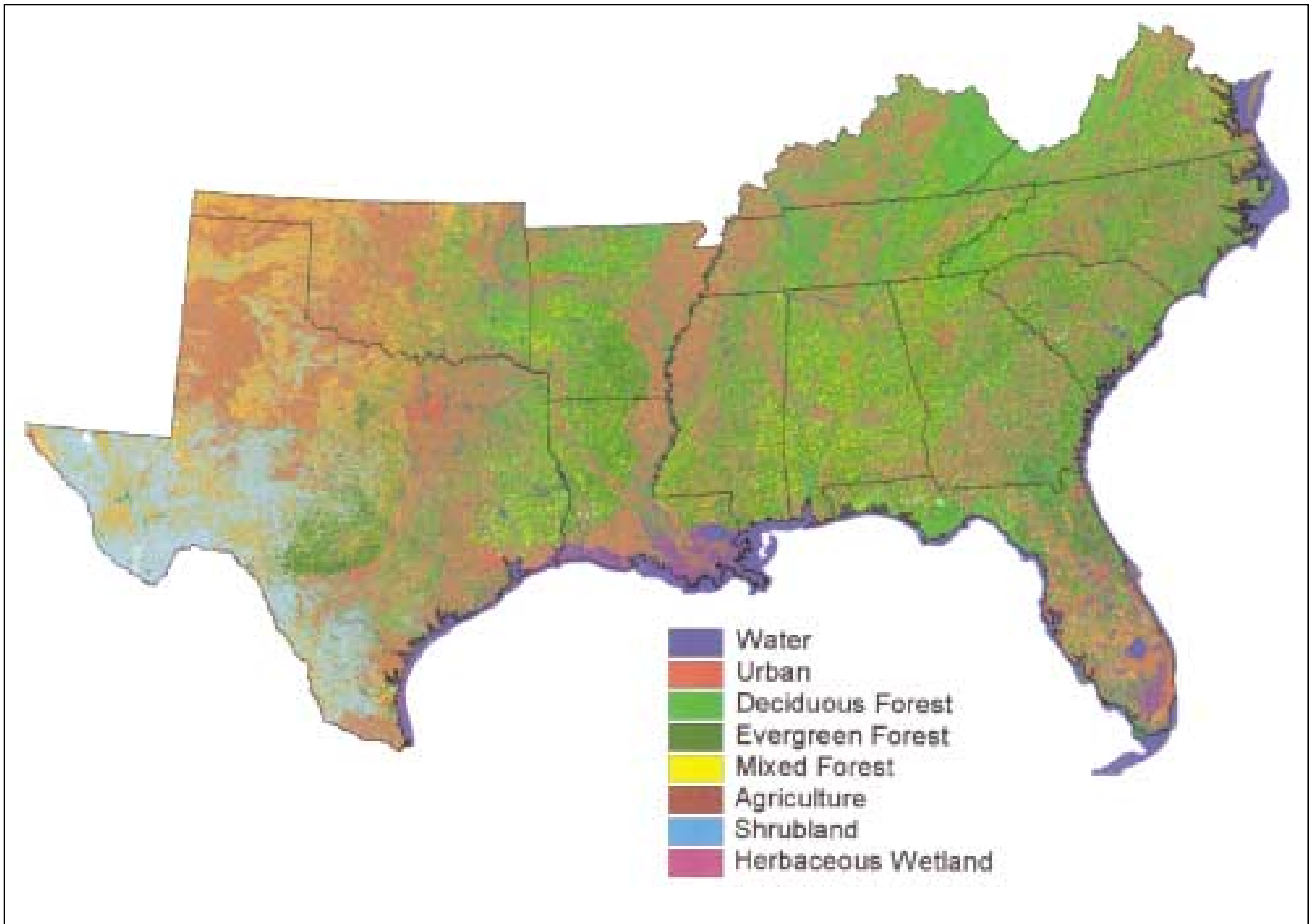

Figure 1. NLCD land cover for the southeastern United States, 1990–1994.

National Land Cover Data set (NLCD). The NLCD-selected TM scenes consist of data acquired between 1990 and 1994. Image processing for the NLCD set has been described by Vogelmann et al.[7] Spectral information from leaf-on and leaf-off data sets was used to derive the land-cover classification products. First-order classification products were developed mainly using 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 conducted using decision trees and visual inspection.

Landsat TM and ancillary data in the NLCD set were acquired for the 13 southeastern U.S. states from MRLC (http://www.epa.gov/mrlc/nlcd.html). Individual state flat land-cover 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 NLCD land-cover classes as follows: deciduous forest (class 41), evergreen forest (class 42), and mixed forest (class 43) (Figure 1, Table 1). The deciduous forest class was supplemented with the woody wetland class (class 91) for a reclassified deciduous forest class.

Forest Productivity Modeling

This study used the physiologically based, monthly time-step process model PnET-II to predict forest productivity and hydrology across a range of climates and site conditions.[8-10] PnET-II predictions of forest productivity have been well correlated with average annual site basal area growth measured across the eastern United States.[11] Input data required by PnET-II include monthly climate parameters, soil water holding capacity (WHC), and species- or forest-type specific vegetation parameters. PnET-II output is dependent on the spatial resolution of input data and includes forest growth, evapotranspiration (ET), drainage, and soil water stress over time. Monthly climate variables required by PnET-II include minimum and maximum air temperature, total precipitation, and solar radiation. The Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) provides these variables for the historic period 1895–1993 across the continental United States at a 0.5° × 0.5° resolution.[12] 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.[13] These climate scenarios, Had2CMSul and CGC1, respectively, include temperature and precipitation effects related to increasing atmospheric CO_2 and SO_4^{2-} aerosols. These data sets 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.[14] This is the finest spatial resolution data set available with such temporal and spatial consistency, so other input data are modified to match the $0.5° \times 0.5°$ resolution for the model.

Soil WHC is derived from the CONUS-Soil data set developed by the Pennsylvania State University Earth System Science Center.[15] PnET-II vegetation variables include foliar nitrogen concentration, light extinction coefficient, and other physiological coefficients or constants derived from field measurements and published literature.[11,14] Based on the climate, soil, and vegetation input data, PnET-II calculates the maximum amount of foliage or leaf area that can be supported.[16] NPP equals total gross photosynthesis minus growth and maintenance respiration for leaf, wood, and root compartments. Respiration is calculated as a function of the current and previous months' minimum and maximum air temperature. 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 carbon 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. ET is equal to transpiration and interception loss. Drainage is calculated as precipitation in excess of ET and WHC. Maximum water storage capacity is determined by WHC to a depth of 100 cm. Monthly ET is a function of leaf area, plant water demand, and climate (i.e., air temperature and vapor pressure deficit). This study reports PnET-II predictions of NPP for evergreen, deciduous, and mixed natural evergreen/deciduous forests. The PnET-II 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 $0.5° \times 0.5°$ resolution, and then Anderson Level II $0.5° \times 0.5°$ forest cover type pixels were assigned NPP values within each $0.5° \times 0.5°$ cell. The resulting estimates of forest productivity across the southeastern United States are stored at a 98.4-ft spatial resolution and include specific forest type attribute information.

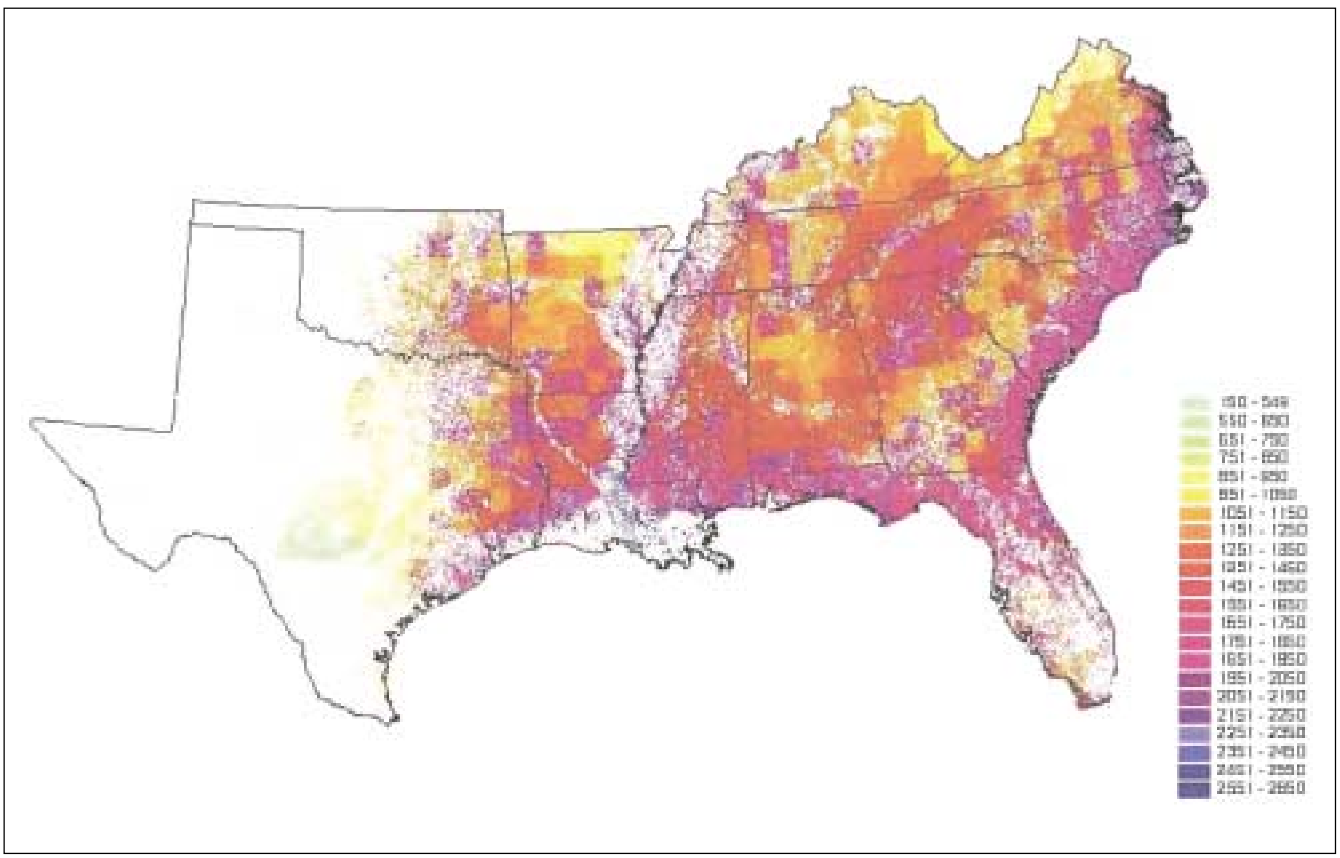

Figure 2. PnET-II model estimation of potential annual NPP (g/m^2/year) for evergreen, deciduous, and mixed forest cover types for the southeastern United States, 1994.

Table 4. Minimum, maximum, and average NPP (g/m^2/year) for forest type (evergreen, deciduous, and mixed) within the 13 southeastern states and the region.

State	Forest Type	Min. NPP	Max. NPP	Avg. NPP
Alabama	Evergreen	1080	1763	1349
	Deciduous	1046	2172	1409
	Mixed	1063	1967	1376
Arkansas	Evergreen	965	1593	1241
	Deciduous	884	2120	1426
	Mixed	814	1846	1315
Florida	Evergreen	1214	2116	1759
	Deciduous	1009	2186	1553
	Mixed	1112	1991	1693
Georgia	Evergreen	1121	1958	1436
	Deciduous	1033	1951	1416
	Mixed	1132	1932	1428
Kentucky	Evergreen	1044	1550	1225
	Deciduous	902	1981	1270
	Mixed	973	1725	1235
Louisiana	Evergreen	1190	2067	1647
	Deciduous	1267	2634	2077
	Mixed	1230	2241	1791
Mississippi	Evergreen	1165	1952	1474
	Deciduous	1254	2531	1674
	Mixed	1209	2241	1575
North Carolina	Evergreen	1166	1910	1548
	Deciduous	1131	2390	1746
	Mixed	1163	2150	1605
Oklahoma	Evergreen	653	1428	1025
	Deciduous	370	1764	1220
	Mixed	683	1571	1114
South Carolina	Evergreen	1142	1924	1483
	Deciduous	1111	2082	1520
	Mixed	1132	1992	1507
Tennessee	Evergreen	1127	1696	1334
	Deciduous	1154	2039	1445
	Mixed	1140	1781	1385
Texas	Evergreen	292	2025	926
	Deciduous	163	2459	995
	Mixed	477	2260	1083
Virginia	Evergreen	894	1801	1237
	Deciduous	769	2337	1303
	Mixed	633	1796	1225
Southeastern United States	Evergreen	292	2116	1289
	Deciduous	163	2634	1425
	Mixed	477	2260	1371

RESULTS AND DISCUSSION

Estimates of Forest Cover and Area from Landsat TM and FIA

FIA statistics of forest land acreages for evergreen, deciduous, and mixed classes were summarized for individual states and the southeastern United States from information compiled for the 1992 Resource Planning Act Assessment, reported by Powell et al.[4] FIA inventories usually focus on forests that are available for harvesting because of the need to provide information on the U.S. timber supply. Little information exists about the 3,048,000 acres of forestland in the southeast that is reserved from timber harvest because of wilderness, park, or other land-use classifications. FIA statistics for forestland were aggregated into evergreen, deciduous, and mixed-forest cover types, and the area was summarized for each forest cover type. Landsat TM classifications in the NLCD set were compared to the FIA areas at the state and regional scales (see Table 3).

Because the FIA inventory defines forest classes at the species and forest-type group level and the NLCD defines forest classes at Anderson Level II, it is difficult to make direct comparisons of more specific forest cover types. Comparison difficulties arose in estimating areas for the mixed-forest cover type. For example, FIA classifies a field plot as a mixed forest type group only if by visual inspection the field crew determines that deciduous or evergreens constitute 25–50% of the stocking on the plot. Forest area estimates at the county and state spatial scales are based on a double sampling that uses either photo points or classified pixels and ground plots. In contrast, forest cover type and area were determined from spectral reflectance characteristics from data collected from a consistent and seamless 30-m grid. The NLCD classifies mixed forest types using leaf-on and leaf-off imagery, baseline clustering with an unsupervised classification scheme, and cluster interpretation and labeling with aerial photography. Texas and Oklahoma posed additional comparison difficulties. The FIA inventories used for this study included data for only 43 of 254 Texas counties and 18 of 77 Oklahoma counties. Counties were excluded from the inventory if they were not classified as having forestland (land at least 10% stocked by forest trees of any size or formerly covered by such tree cover) or if they had insufficient forest area to warrant an inventory of forest resources.

Finally, it should be noted that there is temporal variability in the two data sets. Due to the periodic nature of the FIA forest inventory process, the inventories for the 13 southeastern states span the time period 1988–1995. Acquiring the data for seamless Landsat TM data coverage for the region posed different data acquisition requirements.

The NLCD set required cloud-free Landsat TM scenes for two time periods (leaf-on and leaf-off) for the continental United States. Landsat TM data were acquired from 1990 to 1994 to meet the spectral information and geographic coverage goal of the MRLC. The field plot-based FIA data and the remotely sensed NLCD set represent the best available regional-scale forestland cover data sets available for comparison for this time period.

At the regional scale, there was close agreement in evergreen, deciduous, mixed, and total forestland cover area. The differences between the two data sets, using the TM data as the standard, were –5.64% for total forestland, +0.51% for evergreen forests, –4.70% for deciduous forests, and –19.11% for mixed forests (see Table 3). At the state level, agreement on forestland area ranged from +1.51% for Louisiana to –28.05% for Oklahoma (because of the previously discussed partial FIA sampling for Oklahoma). The sampling error for FIA estimates of timberland ranged from 0.2 to 0.6% at the state level (http://srsfia.usfs.msstate.edu). User accuracy (percentage of time land cover category is correctly identified) for the southeast NLCD set (Region 4) was 56, 64, and 85% for evergreen, deciduous, and mixed forestland cover, respectively (http://edcwww.cr.usgs.gov/programs/lccp/accuracy/appendix.html).

Annual NPP

The pattern of annual NPP for forestlands in the southeastern United States is shown in Figure 2. The spatial patterns of forest production show that the highest NPP in the region for evergreen, deciduous, and mixed-forest types is along the coastal plain of Louisiana. Annual maximum NPP ranged from 2067 g/m^2/year for evergreen forests to 2634 g/m^2/year for deciduous forests (Table 4). The lowest values of annual NPP for all forest types were found at the forest and rangeland ecosystems interface in western Texas and Oklahoma. Minimum annual NPP values in the region ranged from 163 g/m^2/year for deciduous forests to 477 g/m^2/year for mixed forests in Texas. At the regional scale, mean annual NPP ranged from 1289 g/m^2/year for evergreen forests to 1425 g/m^2/year for deciduous forests, with a regional mean for all forestland of 1361 g/m^2/year. The results show that highest productivity of evergreen, mixed, and deciduous forests occurs along the coastal plain, piedmont, and mountain ecoregions, respectively, for the southeastern states.

CONCLUSIONS

We can only hypothesize about the future composition of forest ecosystems because of the effects of global climate change and the socioeconomic responses to that change. The use of field plot-based inventories and remotely sensed data to monitor changes in forest area, composition, and productivity will provide the ability to assess forest contributions to the U.S. carbon cycle from a measurement baseline and then assess changes from that baseline. Historically, the USDA Forest Service FIA has produced area estimates from double sampling techniques. The forestland estimate is then post-stratified into forest types by using the proportion of field plots in each of the forest type strata. Remotely sensed data and image processing techniques provide the ability to assess changes in forest area and composition across spatial and temporal scales for use by local, state, and regional land managers. The incorporation of techniques and methods from traditional forest inventory with satellite imagery is providing unique solutions to the challenge of resource allocation for a periodic forest inventory at the county and regional scales. The relationships established between image spectral responses and field plot-based forest inventories would enable the merging of forest growth and inventory parameters with detailed spatial information. Linking this information with forest growth simulation models could provide estimates of future forest productivity at large spatial scales under predicted climate and forest management activities. The growing interest in the role of forests in the global carbon cycle and as a relatively cheap management option for sequestering U.S. carbon emissions demonstrates the need for reliable estimates of forest biomass and annual production at the regional and national scales.

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