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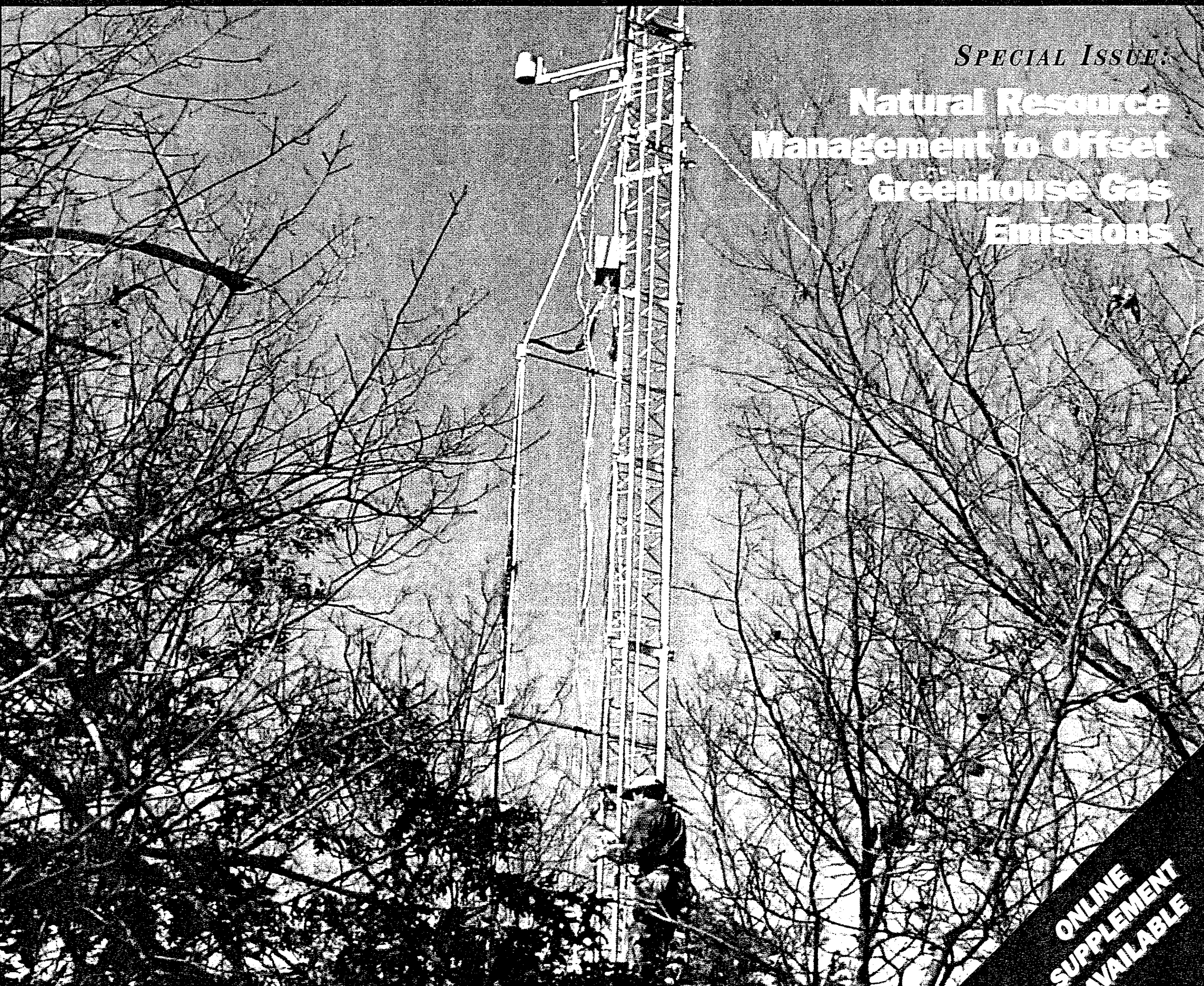

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# Projecting Large-Scale Area Changes in Land Use and Land Cover for Terrestrial Carbon Analyses

**RALPH J. ALIG***
USDA Forest Service
Pacific Northwest Research Station
3200 SW Jefferson Way
Corvallis, Oregon 97331, USA

**BRETT J. BUTLER**
Northeastern Research Station
11 Campus Boulevard, Suite 200
Newton Square, Pennsylvania 19073, USA

ABSTRACT / One of the largest changes in US forest type areas over the last half-century has involved pine types in the South. The area of planted pine has increased more than 10-fold since 1950, mostly on private lands. Private landowners have responded to market incentives and government programs, including subsidized afforestation on marginal agricultural land. Timber harvest is a crucial disturbance affecting planted pine area, as other forest types are converted to planted pine after harvest. Conversely, however, many harvested pine plantations revert to other forest types, mainly due to passive regeneration behavior on nonindustrial private timberlands. We model land use and land cover changes as a basis for projecting future changes in planted pine area, to aid policy analysts concerned with mitigation activities for global climate change. Projections are prepared in two stages. Projected land use changes include deforestation due to pressures to develop rural land as the human population expands, which is a larger area than that converted from other rural lands (e.g., agriculture) to forestry. In the second stage, transitions among forest types are projected on land allocated to forestry. We consider reforestation, influences of timber harvest, and natural succession and disturbance processes. Baseline projections indicate a net increase of about 5.6 million ha in planted pine area in the South over the next 50 years, with a notable increase in sequestered carbon. Additional opportunities to expand pine plantation area warrant study of landowner behavior to aid in designing more effective incentives for inducing land use and land cover changes to help mitigate climate change and attain other goals.

A prominent form of global environmental change is land use and land cover change, and a related change in US forest area in the 20th century involved southern pine in the South. The US South had less than one million hectares of planted pine before 1950, and since then more than 10 million ha of pine plantations have been established on previously nonforested lands or converted from other forest types. Economic, social, and biophysical factors were involved in the changes, influencing landowner behavior. Policy-makers are considering options that include increasing the allocation of the land base growing pine trees in order to increase carbon sequestration in forests. This study provides research findings that could help them choose among policy options.

Many opportunities exist to increase forest growth on the sizable US timberland base, many of which would increase carbon stores (e.g., Hair and others 1996, Vasievich and Alig 1996). Tree planting has been suggested numerous times as a key strategy for increasing terrestrial carbon stores (e.g., Sedjo 1989, Moulton and Richards 1990, Hair and others 1996, Adams and others 1999). Birdsey and others (2000) indicate that afforestation, including pine plantings, can potentially provide the most additional forest carbon sequestration in the United States over the next 10–30 years.

Understanding the role of driving forces in past changes in planted pine area and using scientific studies as a basis for projecting future changes is important when establishing a baseline for global climate change mitigation programs. The baseline can be viewed as "business as usual," in contrast to policy departures that address global climate change. Understanding forces already in place is essential for determining the likely baseline projection of future planted pine area. Historical trends provide helpful guidance in anticipating how drivers such as timber harvesting, agricultural productivity, and population growth will affect area of tree plantations, and how such socioeconomic factors interact with and may impact environmental conditions. For example, economic activities in the forest and agricultural sector influence the amount of planted pine and related land uses and land covers. These dynamics need to be considered when formulating incentive and assis-

KEY WORDS: Baseline; Mitigation; Forest cover type; Carbon sequestration

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tance programs to encourage additional tree plantings designed to reduce carbon dioxide in the atmosphere.

The South also enjoys a cost advantage in that southern pine seedlings (e.g., loblolly and slash pine) need only be grown in nurseries for one year before they are ready for field planting. Currently, high-quality, genetically improved southern pines are available in the South for about US$35–50 per thousand seedlings. In contrast, conifer seedlings in the North (white pine, red pine, and spruces) and West (Douglas fir, ponderosa pine) cost US$150–300 per thousand in the late 1990s. They must be grown for two to three years and may have to be transplanted within the nursery (Moulton 1999). The South's relatively flat terrain is more amenable to mechanical planting (and harvesting) techniques, which also results in lower planting costs than in areas such as the Pacific Northwest.

The behavior of private timberland owners has led to the substantial expansion of pine plantation area in the US South. Private timberlands comprise around 90% of timberland in the South, based on a recent regionwide set of forest statistics compiled for 1997 (Smith and others 2001). Across the South, a proportionately larger amount of forest industry (FI) timberland (39%) is planted compared to nonindustrial private forest (NIPF) timberland (10%). Planted pine is the dominant forest type on forest industry timberlands. The forest industry owned over half of the 12 million ha of planted pine located in the US South in 1997, although NIPF owners possess about four times more timberland in total.

The economic potential for more tree planting is significant, especially on NIPF lands (Alig and others 1999) where 90% of NIPF timberland is currently not planted. The economic attractiveness of tree planting in the South was enhanced by reduced timber harvests on public lands concentrated in the West. Private owners have responded to signals in southern timber markets, where the amount of timber harvest is now greater than for any other country (Wear and Greis 2002).

Expansion of plantation area in the United States is consistent with broad trends in other key timber-growing regions of the world, where plantations increasingly are the source of industrial wood and fiber. Planted forests are projected to provide a majority of the US softwood timber harvest by 2050, although plantations will occupy less than one quarter of the US timberland base (Alig and others 2002a). Plantations in many cases offer timber supply advantages of location, accessibility, operability, wood type, and wood quality. The vast majority of tree planting on private timberland consists of softwood species, mainly because softwoods have long fibers that are desirable in papermaking and they produce larger volumes of higher-value sawtimber in less time relative to hardwoods. Hardwood and softwood species grow at different rates and sequester different amounts of carbon. Thus, the choice of species mix over time is another potential tool in meeting certain carbon storage targets.

Although the area of pine plantations has increased substantially in the southern United States, only about 14% of the total southern timberland is currently covered by pine plantations. The region's timberland area is still dominated by hardwood forest types (Smith and others 2001). More than half of the region's timberland has hardwood cover. Using the broad forest cover types surveyed by the USDA Forest Service's Forest Inventory and Analysis (FIA) unit, the upland hardwood type covers the most area (e.g., oak–hickory), followed by planted pine, natural pine, lowland hardwoods (e.g., elm–ash–cottonwood), and oak–pine forest types.

## Methods

Projections of area changes for planted pine are accomplished in two stages: (1) projections of land use changes, such as a shift from agriculture to forestry (where land use is defined as the purpose to which land is put by humans), and (2) projection of forest cover types, including planted pine, on land allocated to forestry use (where forest cover is the observed biophysical cover on forestland). The projection system is based on biophysical, ecological, and economic criteria, and includes detail on forest ownership classes. In the next two sections, we discuss methods used to project land use changes, and then to model forest type transitions.

### Projecting Land Use Changes

For the South, land use projections were drawn from econometric studies of regional land use changes involving forestry (e.g., Ahn and others 2002). Econometric studies use statistical techniques to test economic hypotheses and develop empirical relationships between revealed landowner behavior, such as afforestation, and explanatory variables such as government programs, timber prices, agricultural prices, and costs of different land management options (e.g., Alig 1986). In the case of land use modeling, the basic approach is to estimate the statistical relationship between the area of land in alternative uses (forest, cropland, etc.) and key determinants influencing land use decisions (e.g., net economic returns to land in different uses), as depicted generically in equation 1 (Ahn and others 2002).

One key variable is population, because anticipated population growth is expected to place increasing conversion pressure on existing forests and farmland (Alig and others 2003). Demands for land in residential, commercial, and industrial uses increase the value of land in these urban and developed uses relative to the value of land in forest or farm use, possibly leading to deforestation. Economic returns or proxies such as population are used in regional models of private land use change based on land rent theory (Alig 1986), where owners are assumed to make decisions that maximize economic measures of land use. These assumptions have generally been corroborated by empirical tests. Other factors are incorporated in these models, including differences in behavior by type of ownership (e.g., industrial versus nonindustrial ownerships), other owner characteristics, and impacts of government policies, such as subsidy programs for afforestation.

$$F_i = f(\textit{population, income, forest return, agricultural return}) \quad (1)$$

where $i$ is the private ownership class and $i$ = 1, 2, or 3.

Separate equations are estimated for two subregions—the Southeast and South Central subregions—which are also used in linked Resources Planning Act (RPA) models such as the one providing projected timber prices (Adams and Haynes 1996, USDA Forest Service 2003). The two subregions have marked differences in land base suitability for uses such as forestry and agriculture, and differing pressures from an expanding human population. The Southeast consists of the Atlantic Coast states from Virginia south to Florida, and they have higher human population densities on average than the eight South Central states (Alabama, Arkansas, Kentucky, Louisanna, Mississippi, Oklahoma, Tenessee, and Texas). As with animals and trees, people are not distributed randomly on the southern landscape. About half of the US population lives within coastal areas (80.5 km from an ocean), and this holds true for the South, especially in fast growing southeastern states such as Florida (USDC National Oceanic and Atmospheric Administration 1999). Florida's growth in human population is part of the South's above-average growth compared to the national average over the last decade. The Southeast also has other fast growing areas such as the Atlanta metropolitan area, with considerable conversion of forests to urban and developed uses, which for carbon accounting can essentially be viewed as permanent reductions. The South Central region is more rural and is the likely location of most of any future net increases in timberland because of net gains from land exchanges with agriculture (e.g., Ahn and others 2002, Wear and Greis 2002). Conversely, the Southeast is expected to experience relatively fast population growth and has had larger reductions in timberland area during the past decade.

Three major private ownerships—forest industry (corporate owners with wood processing facilities), miscellaneous corporate (corporate owners without wood processing facilities), and other private owners—are currently identified in regional data sets. Distinguishing forest ownership classes is important because forest management emphases and intensities can vary by ownership. For example, the class of miscellaneous corporate owners includes timber investment management organizations that tend to manage their timberland more intensively for timber production than the other private class and, on average, have a higher percentage of planted pine (Zinkhan 1993). However, one complication of modeling is a shorter time series of data on miscellaneous corporate ownership compared to traditional classes such as forest industry. We used a time series from 1952 to 1997 to identify determinants of land use changes for forest industry and the nonindustrial private class (Alig and others 2003). We then separated out the miscellaneous corporate ownership from the nonindustrial private forest class using data available from the USDA Forest Service (1988) and Smith and others (2001).

In contrast to the emergence of the miscellaneous corporate class, the farmer class has become less important over time. Alig (1986) earlier used farm forest as one of six forest ownership/land use classes, but the area in that class has notably declined over the last several decades due to occupational shifts, land sales, and other factors. The farmer class in this study is part of the other private class, which also contains other individuals.

Drivers in specific land use equations vary by ownership class (Alig and others 2003). Other private timberland tends to be affected most by population changes and often comprise a high percentage of timberland close to urban areas. Forest industry and miscellaneous corporate owners tend overall to be more interested in investments in timber production, which are affected by timber prices and costs.

Areas of land uses are complied from area-frame surveys of individual land allocation decisions. Forest area equations are estimated as part of a system of equations to capture interactions among land uses on a fixed land base. Their zero sum relationships dictate, for example, that if agricultural land area decreased by more than the increase in forest area in a time period, then urban/other land area had to increase.

Table 1. Trends in area of pine plantations on private timberlands in US South, 1952–1997 (thousand ha) and percentage changes

| Subregion time period | Forest industry | Other private | Total private |
|---|---|---|---|
| Southeast | | | |
| 1952 | 200 | 191 | 391 |
| 1997 | 3018 | 3561 | 6579 |
| Change 1952–1997 | 2818 | 3371 | 6188 |
| % of forest area in 1952 | 3.3 | 0.7 | 1.2 |
| % of forest area in 1997 | 51.4 | 14.4 | 21.6 |
| South Central | | | |
| 1952 | 67 | 153 | 220 |
| 1997 | 2880 | 2032 | 4912 |
| Change 1952–1997 | 2813 | 1879 | 4692 |
| % of forest area in 1952 | 0.9 | 0.5 | 0.6 |
| % of forest area in 1997 | 31.6 | 6.1 | 11.6 |

Parameter estimates in the land use models are used to project major land use areas by decade. Projections of land use areas are based upon external projections of independent variables, drawing upon a common set of macroeconomic assumptions used in the 2000 RPA Assessment (USDA Forest Service 2001), including population and personal income projections. The RPA Assessment documents current resource conditions and trends, and projects future trends (e.g., USDA Forest Service 2001) to establish benchmarks and future milestones for long-term performance indicators. The RPA Assessment utilizes 50 years of historical data as a basis for projections 50 years into the future. The RPA Assessment draws upon more than 70,000 permanent data plots of forest conditions across the United States maintained by Forest Inventory and Analysis units of the USDA Forest Service (2003).

Forestry price projections are from the 2000 RPA Assessment (e.g., Adams 2002, USDA Forest Service 2003) and involve an iterative modeling process with other forest sector models. Iterative runs involve passing back and forth projections of related variables between models such as land use changes and timber price projections until a satisfactory convergence is attained. Constraints are also applied in the land use models based on analysis of historical rates of change, expert opinion, and outside review to preclude illogical or unreasonable area trends for projected land uses/ownerships. Regionwide land use trends are typically not quickly changed or reversed, given the slow rate of change of macro forces at work, capital limitations of owners, and the inertial nature of most land management.

### Projecting Changes in Forest Type Areas

The second stage of projecting planted pine area involves modeling forest type transitions to capture area exchanges with other forest cover types. We used three sets of inputs to project forest cover type transitions for the US South: (1) original state or distribution of forest type areas, segregated by owner and subregion; (2) probability of application of three disturbance categories; and (3) conditional transition probabilities for a forest type's destination in response to receiving one of the three types of disturbance. The conditional forest type transition probabilities are multiplied by the disturbance probabilities and the initial area in a particular forest type for an ownership (equation 2). In equation 2, we show the example of the planted pine type, illustrating area gains and losses linked to other forest cover types.

$$PP_{i,t+1} = \sum_{j=1}^{5} \sum_{k=1}^{3} (D_{i,k,t})(FT_{i,k,t} | D_{i,k,t}\ FC_{i,j,t}) \qquad (2)$$

where $PP$ is the area of planted pine for ownership $i$ at time $t + 1$, $i$ is the ownership ($i = 1, 2,$ or $3$), $j$ is the forest type in the South ($j = 1, \cdots, 5$), k is the type of disturbance ($k = 1, 2,$ or $3$), $D$ is the probability of disturbance type $k$ for ownership $i$ at time $t$, $FT$ is the conditional forest type transition matrix, and $FC$ is the vector of areas of forest cover type at time $t$.

In each time step, timberland gain and loss vectors are used to adjust forest type areas to reflect increments or decrements in area from the first phase of projecting land use changes. The vectors are based on historical probabilities from forest surveys of gains or losses of timberland by forest type and ownership (Table 2). The forest type gain vector describes the allocation of forest types among timberland that is gained from non-timberland land uses. The forest type loss vector describes the allocation of forest types among timberland that are lost to non-timberland land uses. When timberland was gained, it was most likely to be planted pine in the

Table 2. Proportions of private timberland gained or lost by forest type over a FIA remeasurement period, by ownership in US South[a]

| Ownership class and forest type | Gains | Losses |
|---|---|---|
| Forest Industry | | |
| Planted pine | 0.370 | 0.219 |
| Natural pine | 0.149 | 0.245 |
| Upland hardwood | 0.234 | 0.267 |
| Other | 0.247 | 0.268 |
| Miscellaneous corporate | | |
| Planted pine | 0.232 | 0.089 |
| Natural pine | 0.166 | 0.233 |
| Upland hardwood | 0.378 | 0.385 |
| Other | 0.224 | 0.292 |
| Other private | | |
| Planted pine | 0.234 | 0.045 |
| Natural pine | 0.139 | 0.196 |
| Upland hardwood | 0.448 | 0.496 |
| Other | 0.179 | 0.262 |

[a]Proportions are from periodic forest surveys and sum to one for an owner across forest types.

Southeast and upland hardwood in the South Central (Table 2). Upland hardwood and natural pine were the most probable forest types to be lost when land was deforested.

Transition probabilities in the forest type transition matrices are conditional upon three sets of disturbances: no harvest, partial harvest, and final harvest (Table 3). Probabilities of forest type transition in response to each type of disturbance reflect natural successional forces interacting with human-caused activities. The disturbance probabilities and forest type transition matrices represent the major processes affecting forest composition and structure and are a further refinement of the Markov chain method described by Alig and Wyant (1985). Each of these vectors and matrices were calculated from time series of forest survey data consisting of remeasured plots (e.g., Sheffield and Thompson 1997) and were calculated separately for the Southeast and South Central subregions and each private ownership category.

The disturbance probabilities represent the likelihood that a disturbance will occur in a given time period. The final harvest probability vector represents the proportion of area of a given forest type in which all merchantable trees will be harvested in a year. The partial probability harvest vector represents the proportion of area of a given forest type that will be partially harvested in a year. The no-harvest category captures changes due to succession, natural disturbance, and nonharvest human disturbance processes.

A forest type transition matrix is a state/fate matrix that represents the probability of a given forest type (state) becoming a different forest type or remaining the same in a subsequent time period (fate), conditional on a final harvest, a partial harvest, or no harvest. To calculate these matrices, the areas of each state/fate combination were obtained from regional forest inventory data with the state forest types as rows and the fate forest types as columns. For example, one of the elements of the final harvest area matrix for the other private ownership category in the South represents the area of natural pine (state or row) that converted to planted pine (fate or column) following a final harvest in a remeasurement period (Table 3). These area matrices were converted into probability matrices by dividing each element by the row/state total, i.e., the total area of that forest type in the earlier time period.

In addition to the forest inventory based matrices, data from surveys conducted by the American Forest and Paper Association (AF&PA 1999) and Moffat and others (1998) were used in making projections for the forest industry and nonindustrial private owners, respectively. These survey results were combined with inventory-based data to make projections. In particular, based on expert opinion and review meetings, final harvest matrices from the surveys were combined with inventory-based matrices using relative weights of 60/40 and 50/50 for the surveys by AF&PA and Moffat and others, respectively. All other matrices and vectors were based on forest inventory data.

Forest type transition matrices for the no-harvest case showed relatively low annual probabilities that any given forest type would transition to a different forest type across all ownerships and subregions. On average, it takes over 100 years for a forest to transition to another forest type in the absence of a harvest. Oak–pine had the highest annual probability (6%) of transitioning to another forest type. On forest industry lands, planted pine was the most common forest type to which oak–pine transitioned, while oak–pine on miscellaneous corporate and other private timberlands most commonly transitioned to natural pine and upland hardwood. These transitions are a result of oak–pine being a relatively unstable forest type, and slight changes in stand stocking can result in reclassification of the forest type. The mechanisms for these changes include succession (e.g., hardwoods replacing pines on a site) and human intervention, such as chemical applications to control vegetation (e.g., hardwood control in pine plantations).

The probability of a forest type transition following a partial harvest varies by forest type and subregion. Lowland hardwood has the highest and oak–pine has the

Table 3. Distribution of proportions of forest types after disturbance (treatment), by disturbance class for private timberlands in US South, calculated from Forest Inventory and Analysis data (e.g., Sheffield and Thompson 1997)[a]

| Disturbance | Forest type | Planted pine | Natural pine | Oak-pine | Upland hardwood | Lowland hardwood | Nonstocked |
|---|---|---|---|---|---|---|---|
| No harvest | | | | | | | |
| | Planted pine | 0.9154 | 0.0454 | 0.0273 | 0.0052 | 0.0018 | 0.0049 |
| | Natural pine | 0.0645 | 0.8035 | 0.1045 | 0.0169 | 0.0040 | 0.0067 |
| | Oak–pine | 0.1216 | 0.1861 | 0.5541 | 0.1145 | 0.0207 | 0.0029 |
| | Upland hardwood | 0.0338 | 0.0143 | 0.1035 | 0.8112 | 0.0355 | 0.0018 |
| | Lowland hardwood | 0.0099 | 0.0029 | 0.0397 | 0.0598 | 0.8836 | 0.0042 |
| | Nonstocked | 0.2819 | 0.0842 | 0.1076 | 0.3157 | 0.1416 | 0.0689 |
| Final harvest | | | | | | | |
| | Planted pine | 0.5680 | 0.0748 | 0.1351 | 0.1567 | 0.0198 | 0.0457 |
| | Natural pine | 0.2183 | 0.2052 | 0.2147 | 0.2961 | 0.0411 | 0.0246 |
| | Oak–pine | 0.1513 | 0.0673 | 0.2477 | 0.4508 | 0.0700 | 0.0129 |
| | Upland hardwood | 0.1596 | 0.0343 | 0.1451 | 0.6050 | 0.0409 | 0.0151 |
| | Lowland hardwood | 0.1143 | 0.0135 | 0.0552 | 0.1144 | 0.6617 | 0.0409 |
| | Nonstocked | 0.7631 | 0.0000 | 0.0000 | 0.2369 | 0.0000 | 0.0000 |
| Partial harvest | | | | | | | |
| | Planted pine | 0.8197 | 0.0619 | 0.0994 | 0.0122 | 0.0000 | 0.0069 |
| | Natural pine | 0.0238 | 0.5330 | 0.2918 | 0.1404 | 0.0089 | 0.0022 |
| | Oak–pine | 0.0240 | 0.1138 | 0.3916 | 0.4287 | 0.0419 | 0.0000 |
| | Upland hardwood | 0.0011 | 0.0134 | 0.0906 | 0.8489 | 0.0442 | 0.0019 |
| | Lowland hardwood | 0.0000 | 0.0013 | 0.0267 | 0.0668 | 0.9008 | 0.0044 |
| | Nonstocked | 0.0000 | 0.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 |

[a]Sources are represented by the column on the left, and destinations are across the top. The proportions sum to one for a row.

lowest probability of remaining the same forest types following a partial harvest. The oak–pine forest type tends to transition to the upland hardwood forest type, while the other forest types tend to transition to oak–pine. Probabilities of transitions to other forest type following partial harvests of planted pine and natural pine are higher in the South Central subregion than in the Southeast.

Forest type transition probabilities for a final harvest vary significantly by forest type, ownership, and subregion (Table 3) (Alig and Wyant 1985). The lowest probabilities for a forest type remaining in the same forest type after a final harvest are for natural pine. On average, about one fifth of the area of natural pine that is final harvested remains in natural pine across all private ownerships. The highest probabilities of forest types remaining in the same forest type following final harvests are for lowland hardwood and planted pine. Planted pine and upland hardwood are the most common fates for transitions of forest types after final harvest. As for regional and ownership influences, the probability that planted pine would remain in planted pine following a final harvest is much higher in the Southeast and for forest industry and miscellaneous corporate owners. The forest type transition matrices from AF&PA (1999) and Moffat and others (1998) show similar trends to the inventory based matrices, with the exception that the AF&PA and Moffat and others' matrices show higher retention of planted pine and higher transition rates to planted pine.

Given the importance of harvests in forest type transitions, feedback loops in our projections included in-

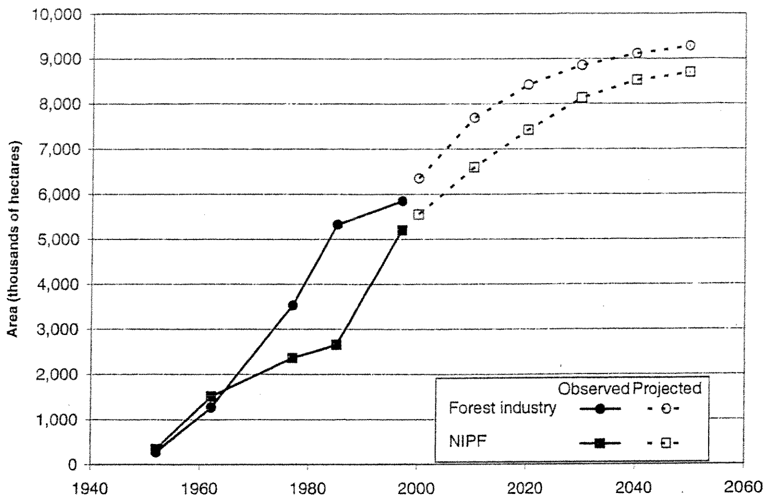


**Figure 1.** Historical trends (1952–1997) and projected (1997–2050) pine plantation area in the South, by private ownership.

corporating disturbance probabilities and market price signals from the national timber supply model that projects timber prices (Adams and Haynes 1996). We adjusted projections of planted pine area at certain time steps if subsequent projections for southern timber prices were significantly higher than used in the original model run. We drew upon recent elasticity estimates from the tree planting study by Kline and others (2002), which give the percentage change in planted pine area for a corresponding percentage change in southern timber prices. The response is inelastic in that the change in planted pine area is less than the corresponding percentage change in southern timber prices. This is true partly because private owners may alter use of other non-land inputs (e.g., fertilizer) in response to timber price changes.

## Results

### Baseline Projections of Planted Pine Areas

Projections of forest type areas from 1997 through 2050 varied by forest type, ownership, and subregion. Planted pine area is generally projected to increase across private ownership groups and subregions. The largest increases in planted pine are projected for the larger South Central subregion. Within the South Central subregion, most of the planted pine will be gained on forest industry lands.

The RPA study projects an increase of roughly 6 million ha in southern pine plantations by 2050 (Figure 1). The area of pine plantations responds over time to projected domestic timber harvest levels and prices and also reflects effects from international markets, such as rising imports that affect prices for southern timber. The RPA Assessment initially projects an increase in softwood prices, but subsequent composite price growth (combined sawtimber and pulpwood) is negative. Softwood timber prices in the RPA projection are the net result of stable sawtimber prices after 2010 and declining pulpwood prices.

Pulpwood prices are influenced by the RPA projection of abundant softwood pulpwood-size material in the South after 2010. The net effect is a softwood price drop after 2010, which thereby somewhat dampens incentives for establishing more pine plantations. This contributes to smaller future additions to pine plantation area compared to the first several decades. Lower price projections in the later decades make pine plantations financially less attractive, and less agricultural land and area of other forest types are converted to plantations. In those decades, projected expansion in pine plantation area would outpace projected changes in timber demand, and timber prices would drop.

The RPA models capture interregional effects of price changes as well as price feedbacks each period. The South Central subregion is the likely location of any future increases in timberland, because of net gains from land exchanges with agriculture (e.g., Ahn and others 2002), while future reductions in timberland area would be concentrated in the Atlantic Coast states. The South Central subregion has more than twice the land area of the Southeast and more potential for expansion in pine plantation area. More than two thirds of the future addition to plantation area is projected to be in the South Central subregion. Actual future outcomes are likely to be sensitive to relative economic returns for forestry versus agriculture in the region, which will be influenced by the timber price projections described above.

Changes in planted pine area due to land use changes include some deforestation due to the growing human population in the South. Urbanization will continue to consume forest and agricultural land as the region's population increases by more than 40 million people. Private timberland area in the South is projected to decline by about 2% by 2050. Rising timber prices, on the other hand, will push some agricultural land toward forest uses. The resulting net loss in southern private timberland area is projected to be roughly 1.6 million ha. As much as 6.5 million ha of agricultural land could be forested by the year 2050.

### Linkages Among Area Changes for Forest Cover Types

Changes over the projection period also reflect linkages among forest types with respect to timber demand. The proportion of hardwood fiber used in pulp and paper-making in the South has increased notably in recent decades, but continued expansion in southern hardwood harvests on the large NIPF ownership is projected to lead to harvest in excess of growth, and therefore to declining hardwood timber inventories after 2010 (Adams 2002). This may cause processors to use more plentiful softwoods in later decades, given the increase in supply due to expanded plantation area.

At the scale of the entire US South, projected directions of change for the areas of other forest types are the reverse for pine plantations: a decrease for each of the natural pine, oak–pine, upland hardwoods, and lowland hardwoods types. The projected decline in upland hardwood area is larger than that for lowland hardwood types and represents a divergence from the longer-term historical trend. Upland hardwoods would be converted to other forest types or to other land uses.

Major trends in forest type areas in the South over the past 50 years are, for the most part, projected to continue over the next 50 years. These trends include an increasing area of planted pine; however, one divergence from the past is a projected reduction in the area of upland hardwoods in the South. Even with such projected changes, hardwoods will continue to dominate the forested landscape of the South. Hardwood forests in 2050 are projected to cover about half of the southern private timberland base, twice the amount of planted pine in the region.

### Influence of Timber Harvest

A key variable in the projection of planted pine area is future timber harvest. In forest ecosystems, human activities represent the most frequent disturbances in most US forests (e.g., Alig and others 2000). Forest management emphases and intensities vary by landowner objectives, forest type, and location. However, notable similarities are evident across ownerships and subregions for final harvest of planted pine. On average, about 2.7% of pine plantations were final harvested or clear-cut over the sample remeasurement period, corresponding roughly to about a 37-year rotation. The annual final harvest probabilities were within 0.2% for all owner–subregion combinations, except the Southeast other private probability that was about one third smaller than the others.

Final harvest and partial harvest probabilities varied across ownerships and subregions. In both subregions, the forest industry and miscellaneous corporate ownerships had the highest harvest probabilities, corresponding to the shortest timber rotations, averaged across all forest types. They were followed by the other private timberland owners.

By forest type, the highest final harvest probabilities were generally observed for natural pine, followed by planted pine. The lowest annual final harvest probabilities were for hardwood types. Within hardwood types, the lowest (less than 1%) was for lowland hardwoods in the South Central subregion.

Partial harvests were more common in the South Central than in the Southeast. In the South Central subregion, the other private owners partially harvested 2.9% of their land per year while the forest industry and miscellaneous corporate owners partially harvested about 2.4% of their timberland per year. In the Southeast, the other private owners partially harvested 0.8% of their timberland per year and the miscellaneous corporate and forest industry owners partially harvested 0.7% and 0.6%, respectively.

America's appetite for timber will continue to grow with a larger population and more economic activity (Adams 2002). Projections are for the South to increase its level of timber harvest, as well as its share of the nation's total, as timber harvests have dropped significantly in the other key timber-producing region, the Pacific Northwest (Figure 2). Between the early 1960s and the late 1990s, the South's share of total US timber removals grew from about 46% to nearly 64% (Smith and others 2001). Changing forest product market and policy conditions in recent years have been associated with marked intensification of timber management on some private lands in the United States and with an increasing share of total harvest being derived from private lands. Between 1986 and 1996, the share of US softwood timber harvests from public forests dropped by more than half, from 26% to 12%. With the decline in US public timber harvest—concentrated in the

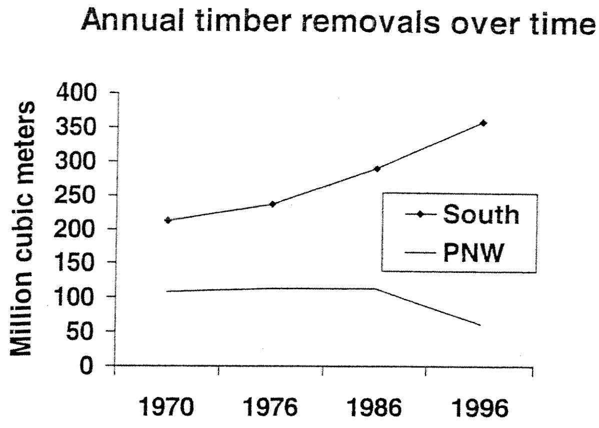


**Figure 2.** Trends in annual timber harvest volumes for the US South and Pacific Northwest, 1970–1997 (Smith and others 2001).

West—beginning in the early 1990s, and given the limited potential for expansion of private harvest in the West, southern timber supplies may be of even greater importance in meeting future demand growth than expected in past studies.

With the overwhelming importance of private ownership, the South has greater potential than other regions for expanding timber growth through intensified management. Private owners have a huge impact on the state of America's forests, especially in the South, as 58% of America's forests and 88% in the South are privately owned, either by individuals, corporations, or other groups (Smith and others 2001). Private timber harvesting is a function of: stumpage price, interest rate, initial timber inventory, and exogenous nonforest income (e.g., noncommodity benefits derive from stock of timber) (Adams and Haynes 1996). The RPA Assessment projects that the annual harvest from US forests will rise by 23% by 2050, due to expanding harvest on private timberlands. The largest portion of the increase is projected to come from softwoods, and the continued expansion in softwood harvest results in an increase in annual softwood removals of 64 million cubic meters between 2000 and 2040 (Adams 2002).

A larger share of timber harvest is projected to come from plantations over the next several decades, increasing from about 20% currently to more than 55% by 2050. In addition to an expanded area of plantations, timber yield per hectare will increase as private owners shift lands to more intensive management regimes. Timber growth will increase under higher yielding regimes, such as those indicated by land management surveys (AF&PA 1999, Moffat and others 1998). At the start of the projections, 21% of industry's planted pine hectares were under high-intensity management. With increased investment, by 2050 that would increase to 80%. A similar but less aggressive pattern is projected for NIPF owners, where higher forms of management comprise about 26% of the planted pine area in 1995 and 49% by 2050. Timber harvests lead to regeneration opportunities, at which time shifts in timber management are most effective. Thus, the RPA assessment projects planted pine growth to increase on average by 98% for industry owners and by 74% for NIPF owners by 2050.

Projected softwood growth continues to rise, propelled by increasing timber management intensity. The increase in growth results in rising softwood inventory. However, softwood removals exceed growth after 2010 in the RPA assessment, but some of this is due to growth not being measured in small trees associated with young plantations.

### Alternative Projection: Climate Change

Policy analysts exploring climate change mitigation strategies are interested in the potential for expanding the pine plantation area beyond the baseline and discovering what incentives would motivate landowners to produce different expansion increments. To investigate the potential size of such increments above the baseline projections described above, we compared baseline projections for the US South with those from a linked model of the forest and agricultural sectors (Forest and Agricultural Sector Model) (Adams and others 1996, Alig and others 1998). Projections of planted pine area by the Forest and Agricultural Sector Model are based on the assumption that owners will pursue economic optimization goals and reflect decisions on optimal forest management investment and land use options relative to agricultural alternatives. Comparing projections based on revealed behavior as in the baseline projections versus optimization projections is important, especially for the nonindustrial private forest owners because they own 49% of the timberland base in the United States and represent a diversity of land use and management objectives.

The baseline projection is for about 5.7 million more hectares of pine plantations in the South by 2040, reflecting a continuation of recent behavioral tendencies by nonindustrial private owners. Projections by the optimization model are more than four times as high, suggesting that southern private timberlands have considerable biological and economic potential for intensified forest management. Other studies have also pointed to a considerable area in the South with biological and economic potential for conversion to pine plantations or other intensified forest management (e.g., USDA Forest Service 1988, Vasievich and Alig

1996). The optimization model accounts for timber price feedbacks, and with its intertemporal optimization framework, the projections include adjustments in timber harvests and plantation establishment over time to maximize the objective function.

No incentives associated with global change mitigation are built into either the baseline or optimal projections. The large increment between the baseline and optimal level of pine plantations reflects forest investment opportunities based solely on financial timber returns.

Potential effects of global climate change on the US forest sector, including impacts on forest carbon inventories, may include adaptation and modifications of growth and geographic distribution of forests. Alig and others (2002b) examined global change scenarios from the National Climate Change Assessment (US Forest Sector Team 2000), based on a combination of global circulation (Canadian and Hadley) and ecological process (CENTURY, Terrestrial Ecosystem Model) models (Irland and others 2001, US Forest Sector Team 2000). The analyses used an equilibrium climate scenario based on transient Canadian and transient Hadley scenarios, with a baseline scenario using average climate for the 1961–1990 period. The climate change scenario was the average of the projected climate for 2070 to 2100. Results include an overall increase in forest productivity in the United States, leading to an increase in long-term timber inventory (Irland and others 2001).

With more forest inventory, timber harvests in most scenarios rise over the next 100 years, lowering timber prices and reducing the area of planted pine in the South (Alig and others 2002b). Areas of planted pine in the South are projected to be smaller in future decades with climate change, as the lower timber prices somewhat dampen incentives for establishment of pine plantations. Other adjustments or adaptations related to market-based incentives include interregional migration of timber production, substitution in timber consumption, altered forest stand management (e.g., change in timber rotation length), salvage of dead or dying trees, shifts in planting stock, and changes in fertilization and thinning regimes.

### Alternative Projection: Biomass Strategies

Other strategies for increasing carbon build-up in forests are short-rotation woody crops (e.g., Alig and others 2000). In additional to traditional tree planting, researchers have also investigated costs and benefits of short-rotation afforestation. Potential impacts of short-rotation woody crops (e.g., hybrid poplar) appear to be large relative to the land area involved because of relatively high amounts of fiber produced per hectare. Although the total US area allocated to intensive, short-rotation woody crops is projected to be a modest portion of the whole agricultural land base (Alig and others 2000), expanded supply of short-rotation crops could reduce traditional forest plantation area in the United States and lead to lower forestland values. In turn, however, lower forestland values could prompt more forestland to be converted for agricultural production to meet expanding world demands for food and fiber.

Other options are afforestation to produce biomass for energy production on a large-scale renewable basis, which could aid in reducing greenhouse gas emissions. McCarl and others (2000) found that the economic attractiveness of biomass energy depends in a key way upon the success of research in developing improved production methods without substantial increases in production costs, in addition to costs of alternative fuels.

## Environmental Management Implications

Determining the effects of land use and land cover changes on environmental conditions depends on understanding past and current land use and land cover practices and projections of future land use and land cover. The projections are affected by population size and distribution, economic development, technology, human institutions, and other factors. Projections of changes in land use and land cover inform environmental decision-making, given the linkage with changes in the climate, carbon cycle, and various ecosystems. Our projections of less US forestland and more developed land form a baseline projection against which policy designers can evaluate US forest carbon policy alternatives, such as expanded tree planting.

Environmental impacts of expanded tree planting could have a range of positive and negative effects. For example, secondary benefits or cobenefits of converting agricultural land to forests via tree planting may be as great as the costs in some cases. Secondary benefits can include reductions in soil erosion and sediment loading, nitrogen runoff and loss, hunting improvements, improvements in biodiversity, and other nonconsumption benefits. This could lead to forestry as a no-regrets strategy.

Forests produce multiple goods and services, and climate change strategies involving tree planting can affect biodiversity and other environmental elements. One example is neotropical birds, many species of which are declining in numbers. The results of Mathews and others (2002) show that assessment of the biological consequences of afforestation for carbon sequestration must consider both current land cover and the distributional patterns of organisms as well as the policy's conversion goal.

Institutions for managing and storing carbon have increasingly been discussed but no national institution along these lines exists currently in the United States. The 2002 Farm Bill did authorize a multimillion dollar forestry program, the Forest Land Enhancement Program, to assist NIPF landowners. The objectives include increasing and enhancing carbon sequestration opportunities. Within our market-based economy, efficient forest carbon management programs would have some key variables: geographic scope, subset of forestry practices and suitable land for each practice, treatment costs and land costs for each practice, and the annual carbon yield for each practice in a specific geographic area. The accomplishments of any terrestrial carbon program would be evaluated against a baseline, including the key component of pine plantations that we examined in this paper. Even in the absence of any incentives or explicit programs to encourage carbon sequestration, the nation is sequestering carbon in its forests. About two thirds of the carbon stored on US timberland is on private lands (Birdsey and others 2000). NIPF lands offer substantial opportunities, including, potentially, millions of hectares of new pine plantations on marginal agricultural land.

Policy-makers need to consider the landowner behavioral aspect and how that may affect actual costs of climate change mitigation practices in our human-dominated ecosystems. For example, what incentives will be required to motivate landowners to get involved and to stay involved in forestry practices such as afforestation that sequester carbon. Evidence from studies of landowners' tendencies to plant trees can aid in guiding mitigation strategies, in that upfront costs such as for site preparation and tree planting tend to overshadow the more time-distant revenues from timber harvests (e.g., Lee and others 1992, Kline and others 2002). Thus, cost subsidy programs may be effective in enticing additional tree planting by nonindustrial landowners. For example, US landowners responded significantly to past government programs for tree planting (Lee and others 1992, Kline and others 2002). A spike in the amount of tree planting in the late 1950s/early 1960s was prompted by a policy to reduce excess agricultural capacity (Alig and others 1980) and a spike in the latter half of the 1980s was due to subsidized tree planting for environmental goals in the Conservation Reserve Program (e.g., reduce soil erosion) (Plantinga and others 2001). The Conservation Reserve Program shifted about 16 million ha of US cropland to alternative cover crops (Plantinga and others 2001). Whether other aspects of forest management, such as rotation age, can be influenced via similar subsidies is open to question.

One question about landowner behavior is whether capital substitution affects the net afforestation area. Lee and others (1992) indicated that such substitution did not appear significant in the US South. That is, private owners were not substituting significant amounts of public capital for their own private capital. If they were, then the net effect would be less tree planting, which would have important implications for any government programs designed to expand the amount of tree planting for objectives such as increased carbon sequestration. A recent study of tree planting by Kline and others (2002) for the same region found some evidence of capital substitution.

The relationship between timber harvests and pine plantation areas used in our baseline projections of planted pine area is consistent with that found by Kline and others (2002). As a basis for projection, NIPF tree planting is projected by Kline and others (2002) to decline gradually in the absence of a significant government cost-sharing program, such as the Conservation Reserve Program. Industry tree planting is projected to rise gradually with more timber harvest, in line with recent timber harvest trends in the US South. Tree planting by industry tends to be more sensitive to prices of forest products compared to the NIPF case. In the 2000 RPA Assessment, the forest industry is projected to add about half of the 5.7 million ha increment in planted pine area in the South, although the rate of increase slows appreciably after real prices of timber fall after 2010. In contrast, timber prices are projected to continue to rise through 2040 in the Southern Forest Resource Assessment (Wear and Greis 2002), and this results in about 3.2 million ha of pine plantations more than in the RPA Assessment projection. The additional pine plantations tie back to the land use projections, as higher timber prices are projected to shift about 3 million ha more of agricultural land to be afforested.

A question regarding afforestation practices and landowner incentives is how long forest practices may be retained by landowners, especially on tree plantings on former agricultural land. Earlier research indicates that owners tend to retain a large majority of government-subsidized plantations well beyond the program date (e.g., Alig and others 1980). The plantations also generally are well stocked with trees and are often regenerated back to forest.

### Unintended Consequences of Policies

Efforts to increase rates of tree planting to notably higher than in the past could lead to unintended consequences. For example, Alig and others (1997) examined the market effects of targeted hypothetical tree planting on agricultural land, to see if "leakage" with respect to policy aims was significant if the amount of tree planting was large enough. Their results indicate leakage via unintended (and unregulated) adjustments in land use between forest and agricultural sectors in response to a sequestration policy can be substantial. Leakage may result when market forces at relatively large scales include price changes in land markets that lead to less net tree planting than envisioned by program planners. Although the area of forested land might increase initially under such a planned scenario, after one full forest rotation much of that land could be converted back to agriculture because of prevailing prices in land markets.

Such countervailing land transfers could substantially blunt the originally intended effect of the policy. Land transfers between sectors must be assessed, since they can tend to mitigate the intended economic benefit effects of policy shifts. Policy design can affect the amount of leakage, but it is not clear to what extent some market-based leakage can be effectively countered.

Those designing any climate change policies need to consider how the interaction of natural and human systems may lead to changes outside the historical range of behavior. Land use and land cover changes can be a driver of environmental and climatic changes. For example, at a larger scale, land use change, such as farming or urban sprawl, has been reported as a major factor contributing to climate change (Cai and Kalnay 2003). Until now, policy makers have focused mainly on how heat-trapping gases such as $CO_2$ are contributing to global warming. However, land surface changes caused by humans may redistribute heat regionally and globally within the atmosphere and may actually have a significant impact on climate. Cai and Kalnay (2003) estimate that about half of US climate warming is due to land use changes. Both urbanization and the growth of industrial agriculture are responsible for more of the rise in temperature across the United States than previously thought.

### Policy Coordination Opportunities

Coordination of tree planting in climate change strategies can include multiple benefits, such as targeting afforestation to reduce atmospheric greenhouse gases, mitigate forest fragmentation, enhance biodiversity, and augment timber supplies. Location of any afforestation programs should be considered alongside programs to slow or arrest deforestation in some cases. For example, urbanization has been identified as the biggest threat facing southern US forests (New York Times 2001, Wear and Greis 2002). Major land use and land cover activities that affect forestry and forest carbon, such as afforestation and deforestation, can be influenced by quite different factors in the economy, which need to be considered in multiprong policy formulation. In addition, the question of who bears the costs and receives the benefits of tree planting brings up the issue of private versus social perspectives. The costs of tree planting and management are largely borne by private citizens in this country, while some of the benefits accrue to a broader group of people if tree planting helps to sequester carbon and address global warming. However, global changes are likely to involve complex natural and human system responses, such that costs and benefits may vary spatially and temporally and could impact parts of the global population quite differently (Alig and others 2002b).

Land use and land cover dynamics for both public and private forestland should be jointly assessed, given differences in average frequencies of timber harvest and other disturbances that affect carbon stores on the land and in products. Given the significant increase in private timber harvests, this had led to a general reduction in private timber rotation lengths, while trees on public lands are tending to become older. Considering human activity in the forest in the framework of disturbance ecology promotes understanding of how natural and human disturbances interact and how that mix differs by type of forest ownership.

Policies should be developed with the multiple environmental attributes in mind. Consideration of the inertia in the economy will also improve effectiveness, including such trends analyzed in the 2000 RPA Assessment: private lands in the eastern United States will be the main source of domestic timber, and pine plantations in South will be the largest source for future increases in softwood harvest (USDA Forest Service 2003). Such extant trends in the national forest sector, along with opportunities to reduce carbon emissions and increase storage by wood substitution, recycling, and improved utilization (Skog and others 1996), will continue to impact climate change mitigation costs, types of forest resources, and biodiversity. Carbon storage and wood production can be joint products, particularly if wood is placed in a long-term use, adding to the environmental benefits of tree planting and prudent use of wood products.

Given the global nature of the issue, many factors need to be considered when seeking the most cost-effective options for climate change mitigation. A multisector view and multiregion perspective would help in identifying comparative advantages and effects on opportunity costs. Other information that may be useful to policy-makers is estimated changes in population and incomes, ecosystem stewardship concerns, and desired levels of human welfare and quality of life. Adaptation and mitigation could occur at the same time (Sohngen and Alig 2000). The scale of consideration is important in that adaptation may sometimes be more of a local response, while mitigation actions or policies may typically be formulated at larger spatial scales. Policy designers should recognize that human-influenced systems can change dramatically over time and can experience economy-wide perturbations (e.g., recession).

With more people populating the landscape, the number of formal studies of land use and land cover changes increased significantly around 1980, with a marked increase in those investigating global climate change over the last decade. Study of revealed landowner behavior has been important for better understanding of both land use and land cover changes, with full consideration of biophysical, ecological, and socioeconomic factors. Individual landowner behavior reflects a very diverse population, and study at aggregate levels has aided in identifying key determinants underlying the large increase in pine plantation area over the last half century. Further research of landowner behavior should include responses to incentives, such as market prices and assistance programs and how characteristics of private owners (e.g., age) influence decisions about land uses and land covers.

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