

U.S. Landowner Behavior, Land Use and Land Cover Changes, and Climate Change Mitigation

Ralph J. Alig

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Landowner behavior is a major determinant of land use and land cover changes, an important consideration for policy analysts concerned with global change. Study of landowner behavior aids in designing more effective incentives for inducing land use and land cover changes to help mitigate climate change by reducing net greenhouse gas emissions. Afforestation, deforestation, reforestation, and timber harvest are the most frequent land management practices that influence forest carbon stocks and flux. Research studies provide estimates of how private landowners respond to market signals and government programs and how they alter land management. For example, landowners have tended to retain subsidized afforested stands well beyond program life in the United States, suggesting that similar programs for climate change mitigation could result in high rates of retention. At the same time, policy makers need to be aware that unintended consequences of policies can lead to significantly different outcomes than envisioned, including leakage possibilities.

Keywords mitigation, adaptation, carbon sequestration, forest sector

Author's address USDA Forest Service, Forestry Sciences Lab, 3200 SW Jefferson Way, Corvallis, Oregon 97331, USA **E-mail** ralig@fs.fed.us

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1 Introduction

Forest ecosystems store about half of all terrestrial carbon (IPCC 2000), and human activities significantly alter land use and forest cover and affect the circulation of carbon and its distribution in terrestrial ecosystems. Millions of forest and agricultural land owners in the United States and other countries are key players in how the world's land base is currently utilized and how it might be used to increase carbon sequestration and help address global climate change (GCC). For example, about two-thirds of carbon stored on U.S. timberland is on private lands, and these private lands offer substantial opportunities for more storage (Birdsey et al. 2000). Whether that potential is realized will depend partially on motivations of landowners and their response to market signals and other incentives such as financial and technical assistance programs. This synthesis of research findings about landowner behavior provides insights into possible responses to market signals and incentives that may prompt landowners to undertake additional carbon sequestration activities.

Land use, land use change, and forestry have received increasing attention in global climate change analyses over the last decade (e.g., IPCC 2000). Experts in forestry, biology, ecology, economics, and related subjects have increasingly investigated human activities that alter land use and land cover. Factors that influence adaptation and the net terrestrial uptake of carbon include the direct effects of land use and land-use change (e.g., deforestation and agricultural abandonment and regrowth) and the response of terrestrial ecosystems to CO₂ fertilization, nutrient deposition, climatic variation, and disturbance (e.g., timber harvest, fires, wind-throws, and major droughts). Direct mitigation strategies include reducing carbon emissions from forests by: reducing the conversion of forests to farmland and other uses (i.e., reducing deforestation), setting aside existing forests from harvest, and reducing biomass burning. Other strategies for increasing carbon build-up in forests are converting marginal agricultural land to forests (carbon plantations, forest product plantations, short-rotation woody crops, or joint product plantations), and enhancing forest management (e.g., Hoen and Solberg 1994). Other

strategies include substituting wood products for more energy-intensive products (Skog et al. 1996; Skog and Nicholson 1998). Research findings can inform decision-makers about GCC adaptation and mitigation possibilities, while recognizing dynamic interactions among climate, ecological, and socio-economic systems and attendant effects on agriculture, forestry, and natural resources.

In a synthesis for non-economists, I first summarize findings from studies of historical trends in land use and land cover affecting forestry that are relevant for GCC analyses, representing actual revealed behavior by landowners. Land use is primarily a socio-economic characteristic of a particular piece of land, describing for what purpose the land is being used and under what condition. Land cover describes primarily the biophysical characteristics of that same piece of land. The rationale of separating land use and land cover is that they are driven by different forces and separating them adds predictive understanding of land cover dynamics, important for any study of future climate change. I examine factors prompting behavior that leads to major disturbances such as afforestation, deforestation, reforestation, and timber harvest. Then, I examine studies that have used such factors in projections to inform society about possible future scenarios for the forest sector. Next, I examine implications of such projections for the carbon situation, given the potential role that sequestered forest carbon may play in helping to mitigate climate change. Related environmental analyses follow, given that forests provide a wide range of benefits to society, including food, fiber, shelter, watershed services, biodiversity, recreation, wildlife habitat, and aesthetic qualities, which may be impacted by GCC land use or land cover changes. I conclude with a discussion of future directions and research needed for improvements in related analyses.

2 Determinants of Land Use and Land Cover Changes

Land use and land cover changes are receiving increasing attention by researchers and policy analysts concerned with global climate change. During the period 1850–1990, net cumulative

global CO₂ emissions from land-use change are estimated to have been 124 Pg C (where 1 petagram [Pg] = 10¹⁵ gram), with about 87% from forest areas and about 13% from cultivation of mid-latitude grasslands (Houghton 1999). In terms of total CO₂ released to the atmosphere worldwide from 1989 to 1998, land use change (primarily deforestation) was responsible for about 20% (IPCC 2000). Land use estimates before 1980 are less precise, and I will focus on land use and land use change estimates since the early 1980s. Land use changes and land cover changes involving disturbances are long-standing topics in forestry and related findings can inform more recent investigations in the global climate change context.

Major land use and land cover activities that affect forestry and forest carbon are afforestation, deforestation, reforestation, and timber harvest. These activities can be influenced by quite different factors. For example, key determinants of deforestation in the United States are change in population and personal income (Alig and Healy 1987). In contrast, afforestation is often a passive activity, in which abandoned pasture land or cropland gradually reverts to trees as plant succession forces are allowed to proceed without intervention (Alig and Wyant 1985). Next, I will examine land use and land cover activities in the United States where land, agricultural, and timber markets are well developed. The United States has had, and will continue to have a significant impact on global forests, and the impact of global forests on the United States is increasingly recognized (Brooks 1993, USDA Forest Service 2003). Such linkages are important when discussing forest-based carbon in a global context.

2.1 Land Use Changes

The size of the forestland base plays a critical role in determining the quantity and quality of outputs from the forests, such as amount of forest carbon. Accurate evaluation of prospective forest policies requires an understanding of the underlying patterns of forest area change and estimates of a policy's impact on future forest area. This includes analyzing components of forest area change, such as afforestation versus deforestation.

With more people populating the landscape, the number of formal studies of land use changes increased significantly around 1980. Modeling approaches to investigate U.S. land use changes in the global change context have been based on earlier studies of private land use in the forestry and agricultural sectors, because about half of U.S. forests are privately owned (Smith et al. 2001). In the forest sector, regional models of private land use change were developed based on land rent theory (Alig 1986), where owners tend to maximize economic measures of land management. Other factors are incorporated in these models, including differences in behavior by type of ownership (e.g., industrial vs. non-industrial private), other owner characteristics, and impacts of government policies, such as subsidy programs for afforestation (Alig et al. 1990).

Econometric studies of regional land-use changes involving forestry in the United States were first based in the southern U.S., which has most of the U.S. forest plantations. 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. The basic approach is to estimate the 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) (Ahn et al. 2000). Alig (1986) estimated empirical relationships between proportions of land in different use categories and socio-economic variables (e.g., population) and land characteristics in the southeastern U.S.

With accumulation of more geographically-referenced land use data, modelers have been able to use spatial data to refine land use models (e.g., Kline and Alig 2001). The models are designed for long-range projecting of future proportions of land in different use categories. Anticipated population growth is expected to place increasing conversion pressure on existing forests and farmland as 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.

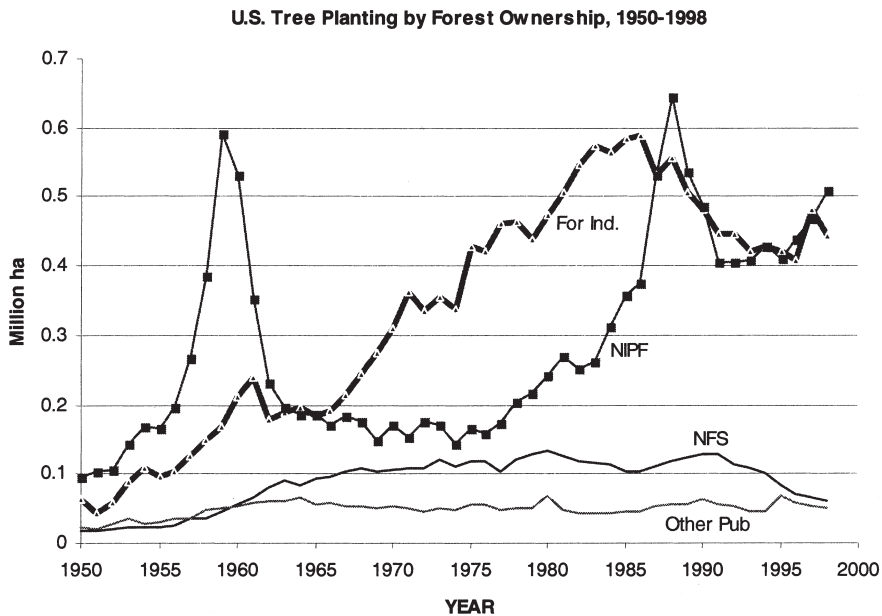


Fig. 1. Tree planting in the United States by ownership, 1950–1998 (source: Moulton 1999).

2.1.1 Afforestation

Econometric land use models are effective tools for projecting forest area (Ahn et al. 2000). Land use models were used in policy simulations to investigate changes in afforestation involving altered assumptions for explanatory variables representing government incentive programs. One example was investigating afforestation options in timber supply analyses (e.g., Alig 1986, USDA Forest Service 1988). Later they were applied to carbon studies, given that afforestation of agricultural land can lead to large increases in carbon capture and storage by the treated area. In the GCC context, these models are particularly useful for policy analysis because they explicitly measure landowner responses to decision variables that can be affected by land use. For example, Plantinga et al. (1999) examined the effects of afforestation subsidies on land use decisions by simulating increases in owner profits from forestry. This provides cost estimates for sequestering carbon in forests. A caveat is that no changes occurred in the underlying structural

relationships, either during the historical period analyzed or the projection period. The model structure is shaped by the policy environment and that can change over time. Statistical tests can be applied to test for changes in model parameters over time (Ahn et al. 2000).

Evidence from studies of private landowners' tendencies to plant trees can aid in guiding mitigation strategies. Birdsey et al. (2000) suggest that afforestation can potentially provide the most additional carbon sequestration in the United States over the next 10–30 years. Upfront costs of tree planting tend to overshadow the more time-distant revenues from timber harvests (e.g., Lee et al. 1992, Kline et al. 2002), so that cost subsidy programs may be effective in enticing additional tree planting by nonindustrial landowners. For example, U.S. landowners responded significantly to past government programs for tree planting, as shown in Fig. 1 by the local spikes in tree planting over time (Lee et al. 1992, Kline et al. 2002). The spike in the amount of tree planting in the late 1950s/early 1960s was prompted by a policy to reduce excess agricultural capacity

(Alig et al. 1980) and the spike in the latter half of the 1980s was due to subsidized tree planting for environmental goals (e.g., reduce soil erosion) (Plantinga et al. 2001).

One question about landowner behavior is whether capital substitution affects the net afforestation area. Lee et al. (1992) indicated that such substitution did not appear significant. 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 et al. (2002) in the U.S. South found some evidence of capital substitution. Projections by Kline et al. (2002) indicate that the amount of tree planting in the U.S. South by the large nonindustrial private forest (NIPF) ownership class could decline in the future without cost-sharing or other subsidies.

In addition 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 potent relative to the land area involved. Although the total U.S. area allocated to intensive, short-rotation woody crops is projected to be a modest portion of the whole agricultural land base (Alig et al. 2000a), expanded supply of short-rotation crops could reduce forest plantation area in the United States and lead to lower forestland values. However, as a double-edged sword from a forestry perspective, it could also allow more forestland to be converted for agricultural production to meet expanding world demands for food and fiber. Afforestation to produce renewable biomass for energy production on a large scale could aid in reducing greenhouse gas (GHG) emissions. McCarl et al. (2000b) found that economic competitiveness of biomass energy depends in a key way upon the success of research in developing improved production methods without substantial increases in production costs.

2.1.2 Reforestation

Reforestation is a key link between land use and

land cover models. Reforestation of harvested forestland can accelerate the natural regeneration process and encourage establishment of fast-growing species. Determinants of reforestation are: timber harvest rates, tree planting costs, land values, interest rates, and cost-sharing programs (Lee et al. 1992, Kline et al. 2002).

If the historical “behavioral trail” is followed in the future, NIPF tree planting is projected to decline gradually. Industry tree planting is projected to rise gradually with more timber harvest (Kline et al. 2002). Major trends in forest cover type areas in the southern U.S. 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 where active reforestation is less frequently implemented (Alig et al. 2002a).

2.1.3 Deforestation

Conversion of forestland to other land uses has deforested more than one-half million ha annually in the United States since 1982, not including forests converted to water-related uses (USDA NRCS 2001). The 1992 to 1997 rate of expansion of urban and developed areas was higher than in previous periods, with forests being the largest source of lands that were developed. Increases in population and personal income have been key determinants of deforestation in the United States (Alig and Healy 1987, Kline and Alig 1999, Alig et al. 2002a).

As with animals and trees, people do not tend to appear randomly on the national landscape. About half of the U.S. population lives within coastal areas (80 kilometers from an ocean) and populations in the South and West have increased faster than the national average over the last decade. Projections show the South’s share of total population increasing, as the Nation’s population expands, with a majority of the U.S. deforestation projected to occur there. Fast growing cities such as Atlanta have seen considerable conversion of forests to urban and developed uses, which for carbon accounting can essentially be viewed as permanent losses. A recent study indicated that

the biggest threat facing southern U.S. forests is urbanization (Wear and Greis 2002).

Projections of deforestation have been based on increasingly sophisticated models. Land use models in the 1980s provided projections of land use change for use in forest sector models, replacing the use of expert opinions about future land use changes. Until the mid-1980s, most timber supply, forest carbon, and wildlife habitat studies have treated quantities of land and natural resources as fixed, or “not explicitly modeled.” However, the reality is that continued shifting of lands between agricultural and forest uses could act to change potential economic returns from land and land prices in both sectors.

Recent projections from such land use models are that the U.S. timberland base in 2050 will be slightly smaller, by about 3%, than it is today (Alig et al. 2002a). Timberland area would decline due to increasing demands for urban and related land uses. Aside from direct conversion to urban uses, timberland is also projected to be converted to agricultural uses to replace developed prime croplands.

Land use models were linked to timber market models, such as the Timber Assessment Market Model TAMM/NAPAP/ATLAS/AREACHANGE system (Adams and Haynes 1996, Alig et al. 2002a) in the United States, to support forest sector analyses. The external land use projection system reflects landowner behavioral tendencies. Later, a linked forest and agricultural sector model, the Forest and Agricultural Sector Optimization Model (Adams et al. 1997, Alig et al. 1998b), had optimal land use and land management as endogenous elements. As just one of many possible objective functions, risk-neutral owners are assumed in the optimization model to be in quest of the highest possible value of returns from their lands into the future. A useful complementary approach for land use projections is to compare projections from both approaches, first examining outcomes for the path of current policies and behavioral trends. Then, use a normative modeling stance to investigate “what if” scenarios including economic optimization, and develop alternative projections based on opportunities to make improvements from society’s perspective. For example, Alig et al. (1999) found a wide range of possible outcomes when

comparing amounts of private tree planting under different scenarios involving assumptions about interest rates and capital markets.

Both the U.S. forest and agricultural sectors are projected to lose land to developed uses (Alig et al. 2002a). In the longer term, continued conversion of rural land to urban and developed uses will act to reduce the timberland base, in some cases removing the most productive lands. Southern U.S. timber harvests have increased significantly recently and the region now produces more timber than any other country in the world (Wear and Greis 2002). The long-term outlook is less certain, with urbanization projected to continue to expand.

2.2 Forest Cover Changes

Forest cover changes result from a combination of ecological successional forces and human activities such as timber harvest and other forest management. A key driver in long term trends in forest cover changes on U.S. private timberlands is timber harvest (e.g., Alig and Wyant 1985, Alig et al. 2001a). Forest type transitions are most common after timber harvest, and also can involve lags in restocking of forests that impact carbon flows and stores.

2.2.1 Timber Harvest

Private harvest is influenced by stumpage prices, interest rates, initial timber inventory, and exogenous nonforest income (Adams and Haynes 1996). Private harvest in the United States over the next two decades will be strongly influenced by current timber inventory characteristics, particularly the limited areas and timber volumes in older merchantable age classes in virtually all regions. Despite these conditions, projections indicate that expanded forest investment would allow some immediate increments in timber harvest, sustained increases in timber inventory, and virtually no long-term trend in softwood log prices (Alig et al. 1999).

The NIPF ownership provides the largest amount of U.S. timber harvest, although many studies point to non-timber objectives of owners.

In aggregate, NIPF timber owners have sustained harvest amounts more than proportional to their share of U.S. timberland area. However, changes in owners can result in a shift in owner objectives and a change in likelihood of timber harvest. Some researchers have noted that a significant number of newer rural landowners have urban backgrounds or are absentee owners (Birch 1994), and some posit that such owners may be less likely to harvest timber in the future than traditional owners.

NIPF owners' responses to incentives about timber harvest, such as delaying harvest, are complicated by many owners not having timber production as a primary goal (e.g., Birch 1994, Kline et al. 2000) and some owners having multiple land management objectives (e.g., Kuulavainen et al. 1996). Fostering the production of non-timber services among such owners with heterogeneous objectives has been the goal of some incentive programs in recent years, such as the Forest Stewardship Program in the United States. At the same time, many owners perceive significant opportunity costs associated with reduced timber harvests, but a mixture of incentive and assistance programs could result in greater joint production of timber and nontimber (e.g., carbon) services (Kline et al. 2000).

Timber harvest is typically the most frequent disturbance on private timberland and can lead to significant changes in land cover. For example, in the southeastern U.S. less than half of final-harvested pine plantations on the large NIPF ownership class are regenerated back to pine plantations, with 54% transitioning to other types: oak-pine (17%), naturally regenerated pine (16%), and hardwood types (21%) (Alig and Butler 2001). Transitions between planted and naturally regenerated stands also involve significant amounts of two-way flows even on the more intensively managed forest industry timberland base in the South. There approximately 30% of pine plantations revert to naturally regenerated forest types after a final harvest. The dynamics are also affected by planting rates, especially on NIPF lands, which can fluctuate notably over time in response to incentives such as government subsidy programs. This has led in the past to important impacts on the regional age class distribution for pine plantations. These findings

suggest that future forests will not be comprised solely of planted stands and involve uni-directional transitions to plantations, and that forest type transitions will influence future forest carbon storage and flux.

2.2.2 *Intermediate Forest Management*

Potential of carbon sequestration in forest biomass through silvicultural management has been examined at the stand level (e.g., Hoen and Solberg 1994) and at larger scales (e.g., Adams et al. 1999, Hair et al. 1996, Plantinga and Birdsey 1993). However, the investment-related linkage among management of existing timber stocks, reforestation, and changing land use has not previously been modeled except in recent timber market models (Alig et al. 1997, Adams et al. 1999). Private forest investment is a critical element in the long-term modeling of U.S. forest resources (Alig et al. 2001b), and is also important in forest carbon analyses (Adams et al. 1999). Projections that account for intertemporal investment decisions linked to harvest timing decisions indicate that U.S. private timberlands have considerable potential for additional wood production and more carbon sequestration under intensified management (Alig et al. 1997). The requisite levels of aggregate private investment would, however, be well beyond those observed in recent years, especially for NIPF owners.

A key component of the potential role of NIPF owners in future carbon sequestration is likely to involve forest investment in the form of plantations. However, restrictions on private forest investment have significant impacts. Thus, a scenario limiting NIPF forest investment to recent historical levels led to significantly lower plantation levels than in an unrestricted case, along with higher log prices and reduced aggregate timber harvest (Alig et al. 1999). The overall impacts from limited NIPF forest investment were notably larger than those from variation in the discount rate. Added forest investment could lead to substantially larger timber harvest volumes and lower prices than those in a scenario that reflects a continuation of recent behavioral tendencies by NIPF owners.

2.3 Key Findings

Some key findings from earlier research discussed above are summarized next. These findings are based on research largely carried out in the United States, however, the findings may be relevant in some cases for other parts of the world.

- 1) Afforestation can potentially provide the most additional carbon sequestration in the United States over the next 10–30 years. Upfront costs of tree planting tend to overshadow the more time-distant revenues from timber harvests, so that cost subsidy programs may be effective in enticing additional tree planting by nonindustrial private landowners.
- 2) Major determinants of artificial reforestation are timber harvest rates, tree planting costs, land values, interest rates, and cost-sharing programs. Currently, most U.S. tree planting is reforestation, where harvested forest land is planted, and may involve the introduction of faster growing tree stock.
- 3) The average annual rate of U.S. deforestation has exceeded 0.5 million ha since 1982. The expansion of urban and developed areas was higher in the 1990s than in previous periods, with forests being the largest source of lands that were developed. Increases in population and personal income have been key determinants of deforestation in the United States.
- 4) Afforestation has offset deforestation in the United States since 1982, with a net increase in U.S. forest area of about 1.5 million ha. However, over the longer historical period of 1952 to 1997 for which only statistics for net area changes in forests are available, there was a net loss of 3.7 million ha of U.S. forest.
- 5) Forest cover changes result from a combination of ecological successional forces and human activities, with timber harvest being a key driver. Timber harvest is the most common disturbance on U.S. timberlands, and notably impacts carbon flows and stores. The dynamics of forest type transitions can involve significant amounts of two-way flows between planted and naturally regenerated stands.
- 6) U.S. private timberlands have considerable potential for additional wood production and more carbon sequestration under intensified management. The requisite levels of aggregate

private investment would, however, be well beyond those observed in recent years, especially for nonindustrial private owners.

3 Projections

Key findings from above are based on examination of revealed behavior as reflected in historical trends, and historical trends provide helpful guidance in anticipating how these factors will behave in coming years. Examining historical trends provides a basis for projecting landowner responses to incentives related to afforestation and other land use activities, and implications can then be drawn for carbon sequestration. The “behavioral trail” to date has included relatively little carbon-centered land management by private landowners. Carbon-related markets in most areas have not developed or are just emerging.

Projections are substantially influenced by assumptions about future values of key determinants, such as population growth and changes in economic activity (e.g., Gross Domestic Product). Demographic reality is that human populations will continue to grow. Historical trends and projections for U.S. population and economic growth both show substantial increases (USDA Forest Service 2001). For example, the U.S. population has increased by more than 100 million since World War II and another 125 million are projected by 2050 (U.S. Dept. of Commerce, Census Bureau 2001). This has fueled growth in urban and developed areas, which have increased by more than 245%. Forest and grassland have lost the most area to developed uses, consistent with the statement in the previous section that changes in those two land uses have contributed the most to net global CO₂ emissions from land-use change.

3.1 Periodic Large Scale Assessments

One source of information on U.S. forest sector trends and forest carbon sequestration and projections is the periodic Resources Planning Act (RPA) Assessments by the USDA Forest Service (e.g., 2001), which document current resource conditions and trends and project future changes.

Table 1. The twelve largest projected changes in forest cover areas in the U.S. between 1997 and 2050 by region, private ownership group, and forest cover type (Alig et al. 2002a, USDA Forest Service 2003).

Region	Ownership group	Forest type	Change	
			Area (million ha)	Percentage
South Central	Nonindustrial Private	Upland Hardwood	-3.1	-19%
South Central	Forest Industry	Planted Pine	2.3	81%
South Central	Nonindustrial Private	Planted Pine	1.8	88%
Southeast	Nonindustrial Private	Natural Pine	-1.4	-28%
South Central	Forest Industry	Upland Hardwood	-1.0	-58%
Northeast	Nonindustrial Private	Elm, Ash, Red Maple	1.0	101%
Southeast	Nonindustrial Private	Planted Pine	0.9	29%
Northeast	Nonindustrial Private	Spruce & Balsam Fir	-0.8	-49%
Southeast	Forest Industry	Planted Pine	0.8	26%
Plain States	Nonindustrial Private	Maple & Beech	0.6	21%
South Central	Nonindustrial Private	Oak-Pine	0.6	12%
Lake States	Nonindustrial Private	Aspen-Birch	-0.6	-23%

This information helps to establish benchmarks and future milestones for long-term performance indicators. The Timber Assessment utilizes 50 years of historical data from more than 70 000 forest survey plots, and make projections 50 years into the future. The Assessment considers the broad workings of the economy, such as a continuing increase in recycling and efficiency in paper production.

3.1.1 Forest Area

Recent projections from land use models applied in the RPA Assessment are that the United States will have less timberland area to support tree growth to sequester carbon, with a net reduction of about 6 million ha by 2050 (Alig et al. 2002a). From a national perspective, the most significant changes in forest cover are projected for the southern U.S. (Table 1). This includes an increasing area of planted pine, due to intensification as the result of regional shifts in timber supply and continuing increases in national and international demand. Conversely, a projected reduction in the area of upland hardwoods is a reversal of historical trends.

However, these net changes only tell part of the story. An examination of the gross changes shows a much more dynamic system. For example, the projected net increase of 5 million ha of planted

pine in the South is the result of a gain of nearly 12 million ha of planted pine and a loss or reversion to other types of approximately 7 million ha out of planted pine.

Other forest area changes that affect cost of forest carbon sequestration are forest fragmentation caused by land use changes. Forest fragmentation has been an increasing concern in some U.S. regions, although data gaps remain regarding the extent and frequency (Alig et al. 2000b). Smaller forested properties may cause some timber management to be uneconomical, and similar cost impacts can hold for forest carbon management.

3.1.2 Planted Forests

Expansion of U.S. plantation area is consistent with broad trends in other key timber growing regions of the world, where plantations increasingly are the source of industrial wood. Plantations in many cases offer timber supply advantages in terms 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. Planted forests are projected to

provide a majority of the U.S. softwood timber harvest by 2050, although plantations will only occupy less than one-quarter of the U.S. timberland base (Alig et al. 2002a).

Although most attention in carbon sequestration analyses has been directed at afforestation and plantations, a mixture of forest-based strategies across a country is desirable. This is particularly true for a land and forest resource base as large as the U.S.'s. Choice of forest species mix over time is a further potential tool in meeting certain carbon storage targets. The forest landscape of the new millennium may have increasing areas of naturally regenerated forests that contribute a declining percentage of the nation's timber harvest, and where harvest could be delayed for carbon sequestration purposes with lower opportunity costs than in other regions or for other forest types. Analyses of carbon sequestration potential will need to account for both the fate of carbon in such naturally regenerated stands, as well as the carbon storage in products from harvested forests. Minimum cost strategies for sequestering carbon in forests should consider the more than one hundred million ha of naturally-regenerated U.S. hardwood forests. For example, the northern U.S. has large concentrations of hardwood forests with economic opportunities to increase carbon stores from a national perspective (Adams et al. 1999).

Policy implications of the smaller amount of past U.S. investment in hardwood timber management are notably different than for the softwood case. In the past 30 years, hardwoods have become a critical part of the overall wood supply picture of the United States, particularly for pulpwood in the South. A trend toward reduced NIPF harvest would have a major impact on timber markets, but could augment carbon stores over a specific time period. Landowner behavior related to hardwoods in recent times includes parcelization of ownerships, changing demographics and owner objectives, and generally reduced interest in timber management. This suggests that future supplies might be augmented by less informal treatment of hardwoods on all private lands. Modest management inputs, or changes in methods, might increase yields to help offset areas shifted out of timber production. Limited hardwood supplies may also justify public and private programs to raise awareness of options in

hardwood silviculture, expand research on more intensive hardwood forest practices, and find silvicultural methods that might achieve both higher carbon stores and amenity outputs with less reduction in timber production.

3.2 U.S. Climate Change Assessment

Potential consequences of climate variability and change, and their effects on forests were examined by the U.S. government and cooperators in a National Climate Change Assessment using a scientific assessment (U.S. Forest Sector Team 2000). In addition to impacts through adaptation, the extent of the U.S. timberland base and its many forest types provide multiple options for responding to market-based incentives from climate-induced changes. Potential effects of global climate change on the U.S. forest sector, including impacts on forest carbon inventories, may include modifications of growth and geographic distribution of forests. Alig et al. (2002b) examined global change scenarios from the National Climate Change Assessment (U.S. Forest Sector Team 2001), based on a combination of global circulation (Canadian and Hadley) and ecological process (Century, Terrestrial Ecosystem Model) models. 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 et al. 2001). At the same time, global warming could increase rice, soybean, and wheat production in some areas (Piekle 2002).

With more forest inventory, U.S. timber harvests in most scenarios rise over the next 100 years, lowering timber prices, and reducing costs of wood and paper products. Total economic welfare is higher than in the base case for all climate change scenarios, due to overall higher forest productivity. Adjustments 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. Aggregate welfare effects of climate change for the forest sector are relatively small, consistent with McCarl et al.'s (2000a) findings that they are relatively limited even under extreme scenarios.

3.3 Implications for Carbon Sequestration

Carbon accounting is essentially in its early stages for large scale efforts, such as to address requirements for the Kyoto Protocol to the Framework Convention on Climate Change. Given the widespread distribution of carbon, studies strive to account for carbon stored both in forest ecosystem components – tree, litter, soil, and understory – and in wood products harvested from the forest. The dynamics of carbon flows and storage are complicated in that forest growth tends to be variable through time, so that the time frame used to report effects will have an important influence on results. Another complication is that carbon contained in forest stands follows multiple pathways after harvest. This requires a view broad enough to cover forest ecosystems, long-term storage of carbon in wood products, and disposal at other sites (e.g., landfills).

Findings from central forestry studies have implications for carbon accounting and analyses. Given that many factors are involved in carbon sequestration, interactions among factors are also important and are likely to become more so as more investigations are conducted. Although the cited studies are largely based in the United States, findings summarized next in some cases can be carefully extrapolated for other regions of the world with similar forest resource or forest ownership conditions, such as for the large NIPF timberland base in Finland.

- 1) Adding another 125 million people in the United States over the next half century may lead to a net reduction in the area of private timberland available for carbon sequestration, with conversions to urban and developed uses outweighing timberland area additions from agriculture. Area of developed area, which would hold relatively little carbon in vegetation, is projected to increase from 39.5 million ha in 1997 in the United States to 72.8 million ha by 2025.
- 2) Forest management will continue to intensify, especially on industrial ownerships, with more timber harvests from the expanding area of softwood plantations. Faster-growing pine plantations in the U.S. South can augment forest carbon stores in a relatively quick manner compared to other U.S. forest types, and also provide harvested products that store carbon. The U.S. trend in intensified forest management is consistent with greater reliance globally on managed forests, private forests, and plantations, along with greater reliance on smaller diameter, more uniform wood raw material. Increased productivity has largely relied on stocking control, site preparation, and tree improvement to date. More productive pine plantations may alter incentives to manage other parts of the U.S. forestland base for timber, potentially allowing more carbon sequestration in some cases if harvest frequency drops and rotations are longer.
- 3) Demand for timber products will continue to grow. The United States has fairly stable per capita consumption of wood and paper products, at one of the highest levels in the world. Storage of carbon in wood and paper products is substantial, as in 1990 approximately 145 Tg of carbon, or 11% of the level of U.S. emissions was harvested and removed from forests for products (Skog and Nicholson 2000). If a substantial proportion of this carbon could be prevented from returning to the atmosphere, it could make a notable contribution to mitigating carbon build-up in the atmosphere.
- 4) The most significant area changes from a carbon sequestration perspective are projected for the Southern U.S., where the majority of the tree planting will occur, along with the conversion of many timberland acres to other uses. Even beyond these changes, the South has the potential to afforest millions of hectares of marginal agricultural land, as well as to economically and substantially increase growth on existing timberlands (Vasievich and Alig 1996).
- 5) Private owners tend to retain a large majority of government-subsidized afforestation and other plantations well beyond the program life (Alig et al. 1980, Kurtz et al. 1996). This means that most carbon in such forest ecosystems is in place for at least several decades. The plantations also generally are well stocked with trees, and are often regenerated back to forest.

- 6) Longer rotations would have some beneficial forest carbon storage and ecological effects, but the economic impacts could include disincentives for landowners if enough other owners decide to participate. An extended forest rotation policy would have consequences for the environment that are not directly associated with the goals of more forest carbon sequestration (e.g., changes in forest cover type areas) (Alig et al. 1998a). Large-scale lengthening of rotations could drive up log prices and increase agricultural prices if agricultural land is converted to forest.
- 7) Unintended consequences of climate change policies should be considered, given previous experiences with other government programs. An example of where forest carbon-related outcomes could vary from the intended aims is leakage. Leakage can happen, for example, 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 (Alig et al. 1997). Although the amount of forested land might increase initially under such a planned scenario, after one full forest rotation much of that land might be converted back to agriculture because of prevailing prices in land markets, thus substantially blunting 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. If leakage is a serious issue at larger scales (Alig et al. 1997), then governments could expend large sums of money in subsidies or other incentives with relatively little net gain in forest carbon or secondary benefits. Leakage in general involves projects or policies having offsetting effects elsewhere, and can originate with a number of land use and management activities (e.g., afforestation, timber harvest, reforestation).
- 8) Terrestrial carbon-related policies can jointly affect both forestry and agriculture, and ecological and economic impacts of forestry and agricultural policies are usually analyzed in isolation (Alig et al. 1998a). Revealed behavior may also highlight hidden linkages and spill-overs within the system. Afforestation policy might alter the use of forest plantations rather than natural forest establishment methods, as well as changing the use of irrigation in agriculture or tillage practices in agriculture if relative costs of carbon storage in the two sectors are altered. Interregional effects of large-scale policies can also be substantial, as a zero-timber harvest policy for public lands in the western U.S. could notably impact the level of forest investment, timber harvests, and carbon storage for U.S. southern timberlands.
- 9) Different payment mechanisms have been proposed in the literature to provide incentives for landowners to sequester carbon in forestland. Some payment mechanisms may be adapted more easily than others to include forest carbon. These mechanisms include renting land (as in the current USDA Conservation Reserve Program), paying only for land use change, renting carbon directly, and other methods. See Sohngen et al. (2002) for a discussion of the relative efficiency of a number of different payment proposals in terms of their potential to maximize forest carbon sequestration. In the United States, such programs are often directed at nonindustrial private forest owners, who tend to respond more to reduction of upfront afforestation costs than prospective timber returns (Kline et al. 2002). While this ownership class has also harvested timber at aggregate levels more than proportional to their share of the U.S. timberland base, in general such owners have opted for relatively low levels of timber management investment, especially for the large hardwood resources (Alig et al. 1990). Potential to expand timber production and carbon storage in forests is large for this ownership (Alig et al. 1999, Vasievich and Alig 1996).
- 10) Private owners often manage their lands for multiple objectives (Birch 1994, Kline et al. 2001). The diversity of private owners has led to many patterns of behavior and resultant forest conditions. This includes some stands of timber well beyond the standard timber rotation, reflecting utility for non-timber values such as amenity attributes, wildlife habitat, and others (Pattanayak et al. 2002). Carbon sequestration is a relatively new objective and carbon markets are typically non-existent or just emerging.

3.4 Implications for Other Forest Ecosystem Attributes

Some of the findings above have broad implications, affecting timber supply, biodiversity, and

other ecosystem goods and services. Implications of carbon sequestration activities for non-timber ecosystem attributes have been receiving more attention (see, for example, URL http://www.efi.fi/events/2002/Forest_Carbon_and_Biodiversity/frame_conference.htm), but currently are not as well documented in the literature as for timber-related elements.

Biodiversity could be impacted in a positive or negative way, depending on what specific scenario out of many is considered involving future carbon sequestration. Planners also need to recognize that some approaches may be complementary, such as delaying or essentially eliminating harvest to protect endangered species. However, in the longer term, dynamics of natural ecosystems could lead to changing relationships. In natural forests, disturbances are caused by such factors as fires, storms, insects, pathogens, floods, and animals. However, with more people on the national landscape, in many forests human actions at an accelerating rate are replacing or dominating natural disturbances. Human modification of forest structure to meet management goals, such as production of timber, has often been successful in creating desirable joint production of goods and services.

4 Policy Design Considerations

In the United States to date, policy design for carbon sequestration has been more conceptual in nature than actual implementation. Given the joint production nature of forest ecosystems, carbon-related policies have the potential to usefully augment existing or future policies, and can have a positive effect on forest ecosystem stewardship. However, it is important to recognize the need to integrate carbon-related policies with others.

4.1 Integration of Carbon Sequestration with Other Policies

Potential actions for reducing net greenhouse gas emissions include a wide variety of sinks and sources. A wide range of strategies could increase the storage of carbon in forests and forest products (Birdsey et al. 2000, Sohngen and Alig

2000), and many would impact forest ecosystems in other ways. Opportunities to integrate carbon sequestration policies with others include enhancing biodiversity, as discussed next.

4.1.1 *Multiple Objectives in Afforestation Policy*

Forests produce multiple goods and services, and climate change strategies can affect biodiversity and other environmental elements. For example, afforestation incentives could be targeted to jointly reduce atmospheric GHG's, mitigate forest fragmentation, enhance biodiversity, and augment timber supplies, or some other combinations of those items. Investigations of co-benefits of tree planting have moved beyond statements of "no regrets" to striving to document multiple benefits of afforestation and other tree planting.

In the case of afforestation as one policy tool, a possible biodiversity advantage could be in the form of enhanced populations of forest species that might result from afforestation. One example is neotropical birds, many species of which are declining in numbers. Matthews et al.'s (2001) results 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 land-use conversion goal.

4.1.2 *Strategies Across Mixed Ownerships*

Institutions for managing and storing carbon have increasingly been discussed but no national institution along these lines exists currently in the United States, either for public or private lands. Potential activities on both U.S. public and private forestland should be jointly assessed, given differences in biodiversity across ownerships. In addition, ownerships also differ with respect to frequencies of timber harvest and other disturbances that affect carbon stores on the land and in products, as well as biodiversity. It is not new to the United States to pursue policies with both ecological and economic objectives. Consider the common goals of improved water quality; timber, fish, and wildlife habitat; recreational opportunities; erosion con-

trol, and more. But while policies affecting public forestlands get the most press, the largest part of U.S. timberland, about 75%, is privately owned, and the responses of these owners are also important considerations for policy makers.

Another reason to jointly consider both public and private forests is their linkage via markets. For example, reductions in U.S. public timber harvests can lead to significant changes in market signals for private owners (Adams et al. 1996). The same is true for producers in other countries, such as the response in tree planting in New Zealand in the early 1990s when U.S. National Forest harvests dropped substantially due to protection measures for the spotted owl and other endangered species.

Policies should be developed with the multiple environmental attributes in mind and with a broad systems view. Science-based assessments can inform policy analyses of environmental, social, and economic costs and benefits of climate change response strategies. The systems view includes policy considerations at both temporal and geographic scales. Changes at both scales involve a human ecology portion that includes physical patterns observed on a landscape. The economics portion involves consideration of private versus social viewpoints, in that some effects are external to private producers and consumers' outcomes. The bulk of research examining possible impacts from global warming has been biophysical in nature (e.g., Neilson and Marks 1994). Integrated assessment approaches to studying land use and land cover dynamics are crucial to analyze more than just the direct or first-round effects of policies targeted at improving environmental conditions, with consideration given to coordinated policies.

5 Future Directions

Billions of decisions about land use, forest management, and response to climate change policies will be made over the next several decades. Improved decision-making will depend partially on better carbon models, but also on better integration of socio-economic research findings, because of the importance of human actions in

adaptation and mitigation. Feedback within the system of models – global circulation and climate, terrestrial ecology and forest growth, and human activities – and biodiversity valuation warrants more attention in future research.

Science pertaining to climate change has evolved substantially over the last decade. However, at present, estimates of impacts of climate change on forest and carbon yields have a wide range of uncertainty (Sohngen et al. 1998). Part of this uncertainty involves land use change, such as farming or urban sprawl, which has been reported as a major factor contributing to climate change (Pielke 2002). Until now, policy makers have focused mainly on how heat-trapping gases such as CO₂ are contributing to global warming. However, Pielke (2002) found that land surface changes caused by humans in places such as North America, Europe, and Southeast Asia, may redistribute heat regionally and globally within the atmosphere and may actually have a greater impact on climate than that caused by the combined effects of greenhouse gases. As new findings accumulate, these can be utilized in scenario analyses to help place in perspective different sources of uncertainty and how they affect projected outcomes.

Future developments in other sectors are likely to continue to impact the forestry sector and its potential for carbon sequestration. Forestry's potential role in climate change mitigation is still under debate, as earlier studies suggested a massive program would be necessary to have notable impacts (e.g., Sedjo 1989). If substantial resources from the forest sector are dedicated to climate change mitigation, this would increase the importance of considering capital constraints and possible capital substitution. Sufficiently large programs could also warrant closer monitoring of interactions with the agricultural sector. This includes proposed reduction of agricultural subsidies, and associated effects on forests as a competing land use. Agricultural policies may be one of cycles and unforeseen fluctuations if the future follows historical trends. The multi-sector view should include the energy sector and interactions with the forest sector that affect opportunity costs of net GHG reductions by the forest sector. This includes consideration of increasing carbon stores not just in forest ecosystems but also in

harvested wood products, and improvements in extending the time over which the harvested wood remains in use.

The lens through which we view – and judge – transformations of our landscapes can change from generation to generation. Decision science involves examining alternatives and trade-offs among alternatives, and unforeseen dynamics in natural and human-based systems imply that no sole optimal “sustainability” alternative will necessarily persist through time. Future efforts to promote forest sustainability will be impacted by what happens under the Kyoto Protocol to the Framework Convention on Climate Change, and significant uncertainty surrounds that social aspect of global climate change.

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