MEETING GLOBAL POLICY COMMITMENTS

Carbon Sequestration and Southern Pine Forests

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ABSTRACT

In managed forests, the amount of carbon further sequestered will be determined by (1) the increased amount of carbon in standing biomass (resulting from land-use changes and increased productivity); (2) the amount of recalcitrant carbon remaining below ground at the end of rotations; and (3) the amount of carbon sequestered in products created from harvested wood. Because of the region's high productivity and industrial infrastructure, carbon sequestration via southern pine forests could be increased, and this may benefit the nation in terms of global policy commitments.

Keywords: carbon sequestration; southern pine forests

Atmospheric carbon dioxide (CO_2) concentration is increasing at approximately 1.4 parts per million (ppm) by volume per year. Because CO_2 acts as a greenhouse gas, trapping exiting solar radiation, there are concerns that these increases in atmospheric CO_2 will result in climate change. Annual anthropogenic carbon emissions in the United States total approximately 1.7 billion tons (Marland et al. 1999). Recently, there has been increased international pressure to reduce net carbon emissions in the United States and around the world.

One potential mechanism for reducing net carbon emissions is through increased carbon sequestration into forests. In a large-scale assessment, Birdsey and Heath (1997) estimated that over the past 40 years, US forests have sequestered enough carbon to offset approximately 25 percent of US emissions. Managed southern pine forests have played a large role, steadily increasing in land area over the past half-century. The South represents about 24 percent of the land area of the United States; outside of Texas and Oklahoma, about 58 percent of this land is forested and about 20 percent of the forestland is owned by forest industry. From 1962 to 1992 the total land area of commercial pine forest rose 27 percent to 27.9 billion acres (Powell et al. 1993). The extent of managed forests has increased because southern pine forests are extremely productive. The warm climate of the South extends the growing season and reduces rotation length; pines reach sawlog size in 25 to 35 years on many southern sites (Schultz 1997). Intensive management of southern pine plantations, using competition control, fertilization, and superior genotypes, can now increase productivity three-fold (Borders and Bailey, in press).

In managed forests, the amount of carbon further sequestered will be determined by three factors: (1) the increased amount of carbon in standing biomass, due to land-use changes and increased productivity; (2) the amount of recalcitrant carbon remaining below ground at the end of the rotation; and (3) the amount of carbon sequestered in products created from the harvested wood, including their final disposition. Therefore, managed southern pine forests sequester carbon both *in situ* (biomass and soil) and *ex situ* (products). *Figure 1* displays a simple model useful in conceptualizing carbon sequestration in southern forests.

Carbon sequestration via southern pine forests may benefit the United States in terms of global policy commitments. However, there are many major methodological issues—such as what carbon pools to include, how to deal with events such as fire and pest outbreaks, how to deal with carbon "leakage" from systems—that require international political agreement before carbon credits become a reality. The purpose of this article is not to enter into this political debate but instead to provide a framework for quantifying the ability of southern pine forests to sequester carbon. Here, we first assess the magnitude and primary controls of the major carbon pools. We then suggest management options for increasing carbon sequestration and research needed so that southern pine forest carbon sequestration can be better quantified, predicted, and managed.

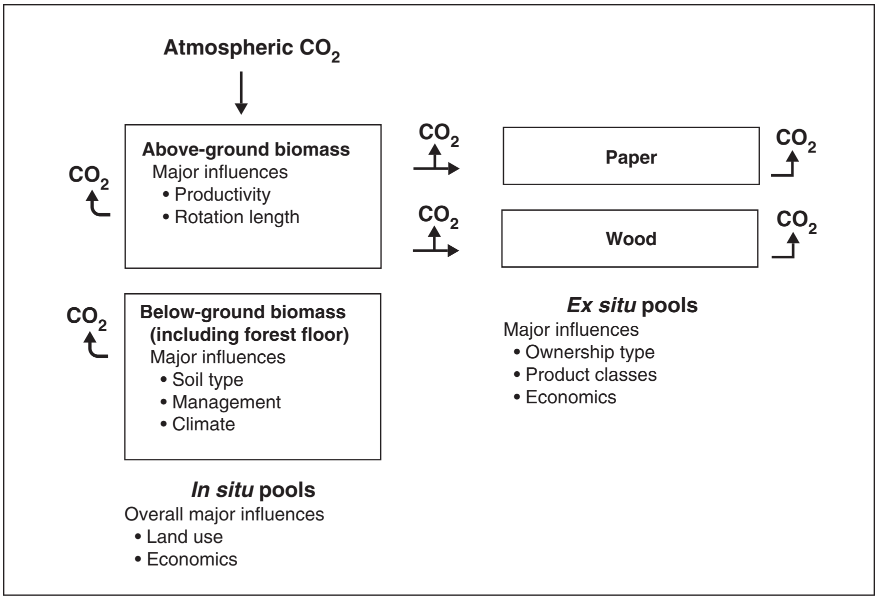

Figure 1. **Conceptual model of carbon sequestration via southern pine forestry.**

Land Use: A Major Determinant

Two primary forces determine land use in the South. One is economic development that generates demand for urban, residential, and other human-dominated land use; the other is the relative economic returns from agriculture and timber. The margin between agriculture and forest land use is uniquely elastic in the South. Over the past 20 years, forest areas have shifted into developed and urban uses and a substantial area of agricultural land has shifted back to forest; on net, the area of forests in the South has remained relatively constant over the past 40 years. However, the distribution of forest types has changed substantially. Increased pine plantations have steadily offset declines in the area of natural pine. Natural pine has declined from about 72 million acres in 1952 to roughly 34 million acres in 1998, while plantations now comprise more than 32 million acres (about 16 percent) (USDA Forest Service RPA data; see also Powell et al. 1993).

Economic land-use models project that, with stable agricultural prices, shifts to forestland from agriculture will continue to offset urbanization. Urbanization will be concentrated largely in the Piedmont and coastal areas, while expanding forest cover is expected in the Coastal Plain, the most productive region for growing pine. It is estimated that the area of planted pine may double to more than 60 million acres by 2040, mainly through planting on marginal agricultural land (Murray et al., in press).

How Is Sequestration Estimated?

Before we delve into the controls of carbon sequestration per unit land area, we will briefly discuss how these estimates are attained. Essentially, carbon sequestered by forests is the difference between carbon gained by photosynthesis and carbon released by respiration of all the components of the ecosystem; this overall carbon gain or loss is called net ecosystem productivity (NEP). In the past, NEP could only be estimated by measuring component processes on one or a group of sites and then summing the component values *(table 1, p. 16)*. More recently, technology and theory have developed so NEP can be estimated "directly" (some modeling is needed) in a method called eddy covariance. Besides the exact measurement protocols, sampling intensity and extent also can differ widely.

Annual NEP of forests in the southeastern United States, measured with eddy-covariance instruments, tends to be higher than that in forests elsewhere in North America, reaching values above 4,460 pounds of carbon per acre per year (Clark et al. 1999). Such high NEP values are supported in the Southeast by mild climate, ample precipitation during the growing season, and the presence of fast-growing species. Unlike most broadleaf species, most coniferous species are able to absorb CO_2 nearly year-round under favorable climatic conditions. Over two years, eddy covariance measurements at a 14-year-old loblolly pine *(Pinus taeda)* stand at the Duke Forest in Durham, North Carolina (located in the northern third of the species range) showed positive NEP in nearly all months of the year *(fig. 2, p. 17)*. The annual NEP at this forest was estimated between 5,620 and 6,780 pounds of carbon per acre per year (Katul et al. 1999), similar to estimates in a Florida slash pine *(Pinus elliottii)* plantation (Clark et al. 1999). Some of the variability in NEP was due to stress from strong periods of drought (Oren et al. 1998).

Using the mean annual NEP at the two monitored southern pine forests (6,110 pounds per acre), and the area covered with southern pines in the Southeast (795.9 × 10^3 square miles), we estimate annual NEP in southeastern pine forests should be in the order of 0.21 Pg per year (P = 10^{15}; 0.187 × 10^{15} pounds per year). This NEP estimate represents a gross approximation of the upper limit for the southeastern pine forests at their current extent and equals approximately 12 percent of the annual US fossil fuel emissions. This estimate does not include the growth of mixed hardwood-pine forests. In addition, the estimate does not account for the impacts of fires, harvesting, and other biotic and abiotic perturbations. Lastly this analysis assumes that all pine forests are at the same highly productive developmental stage represented by the two monitored

Table 1. Methods for quantifying CO_2 budgets in forest systems.

Sampling method	Purpose	Description	Pros	Cons
Eddy covariance	Determines the total stand carbon flux.	Micrometeorological technique based on the principle that eddies displace gas parcels from the soil surface to some measurement height. Measurement apparatus consists of a tower equipped with sonic anemometers and CO_2 analyzers.	Integrates carbon efflux over large areas (stand level). Measures continuously when weather conditions permit.	Gas exchange in trees or shrubs can interfere. Cannot assess small treatments or plots.
Component analysis				
Long-term sampling				
Harvest and soil carbon analysis	Determines carbon sequestered in soils and trees.	Measures above- and below-ground biomass over long periods of time using silvicultural mensuration and soil cores. Core samples are analyzed for carbon content and quality.	Can be used for component analysis. Can separate carbon stored in soil and trees. Very detailed carbon analysis for the long-term plot.	Usually expensive to install and maintain long-term studies. Study area of limited size. Data may only relate to limited geographic area or management type.
Short-term sampling				
Carbon efflux measures	Determines quantity of CO_2 produced. Can be separated into soil and root components.	Measures CO_2 efflux in chambers placed on the soil surface or around roots using automated system. Many chambers can be attached to the base unit and monitored continuously.	Can be used for component analysis. Can assess small treatments or plots. Portable; can move to many different sites or treatment plots.	Potential for chamber effects to alter soil or root surface conditions. Difficult to partition total flux into autotrophic and heterotrophic components.
Harvest and biomass analysis	Determines total quantity of carbon sequestered in trees.	Assesses above- and below-ground biomass.	When combined with CO_2 efflux, provides a more complete quantification of carbon budget. When used in this fashion it can be determined if a site, treatment, or management practice is a source or sink of CO_2.	Labor intensive. Destructive sampling.

stands used in the estimate. (Note: Although at a productive *stage* of growth, the measured Duke Forest stand is not highly productive, per se, as it has a site index of 43 feet, base age 25.)

Below-ground Carbon

Quantitative understanding of below-ground carbon dynamics is particularly important to managing forests and long-term carbon sequestration. Below-ground carbon resides in three components: root biomass, forest litter, and mineral soil.

Root biomass. The growth and development of forests includes the accretion of about 15 to 20 percent of the total organic matter in root biomass. In southern pine forests, most root accumulation is in large, woody tap and lateral roots, with relatively small fraction of the biomass accumulating in fine roots. At the Calhoun Experimental Forest in South Carolina, 46.4 tons per acre or 94.3 percent of the total root biomass was estimated to be in coarse woody laterals and tap roots over 34 years of pine forest growth. Following harvest, although fine roots may disappear rapidly (Richter et al. 1999), woody tap and lateral roots may decompose slowly. Van Lear et al. (1995) estimated that 13 years after logging in an upland Piedmont site on clayey soils, about 19 percent of the carbon in tap and lateral roots was still below ground. As rotation length decreases, the amount of carbon present in residual tap roots should increase.

Forest litter. More is known about the carbon deposited in litterfall and accumulated in the forest floor. In southern pine forests, carbon accumulates rapidly in a heavy blanket of forest floor. In the first several decades of pine growth, the forest floor or soil O horizon may contain 34 to 78 tons per acre of carbon. This material contains not only large amounts of carbon but also of essential nutrients as well, espe-

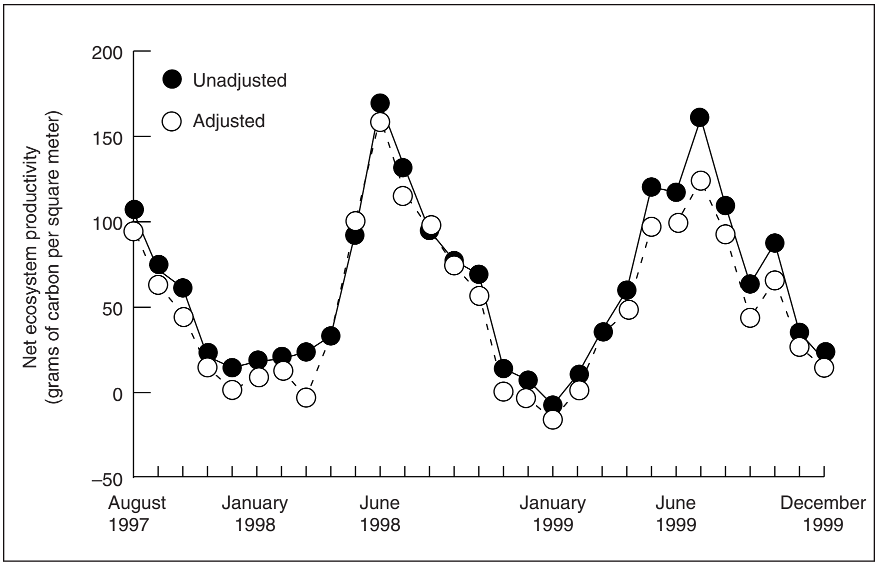

Figure 2. **Monthly sums of net ecosystem carbon productivity (NEP) over a loblolly pine plantation at the Duke Forest. Positive NEP values represent uptake by the forest, whereas negative values indicate that release from decomposition and plant respiration is greater than net photosynthesis. Adjusted values represent estimates corrected for ecosystem respiration under stable nighttime conditions. Note that the drought during June 1999 drastically reduced carbon uptake relative to the previous June.**

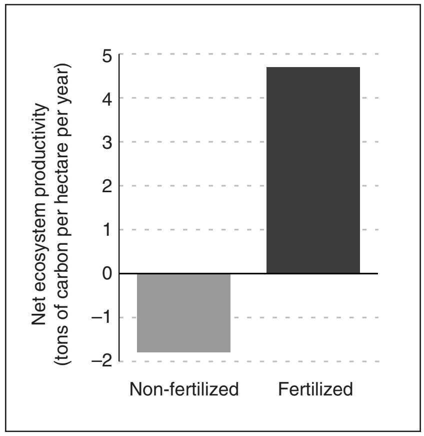

Figure 3. **Net ecosystem productivity developed from component analysis for nonfertilized and fertilized 11-year-old loblolly pine plantations growing at the Southeast Tree Research and Education Site (SETRES), Laurinburg, North Carolina. The results are for the 1995 growing season, after four years of fertilization treatment. *Source:* Maier and Kress (2000).**

cially nitrogen and phosphorus. Compared with forest ecosystems dominated with deciduous hardwood, the decomposition of pine litter is slow. Jorgensen and Wells (1986) estimated that nearly half of the needlefall carbon was present in the forest floor five years after being deposited. Following forest harvest, however, decomposition of this forest floor material is rapid. Logging slash is also added to the forest floor during harvest, and estimates indicate that while foliar materials are decomposed relatively rapidly, decomposition of large woody debris is limited by moisture conditions (Barber and Van Lear 1984; Tiarks et al. 1999) and may contribute to medium-term carbon storage.

Mineral soil. Mineral soil carbon includes only the finest carbon fractions that would pass through a 2 mm sieve or the carbon that adheres to soil mineral matter. The accumulation of organic matter in the mineral soil of southern pine systems can be slow due to relatively high decomposition rates of new carbon inputs (Richter et al. 1999). These dynamics are strongly controlled by soil physical properties such as clay content and porosity. A number of estimates of decomposition indicate that although most new carbon inputs to mineral soil may be decomposed quickly, the small fraction of residual organic material is relatively difficult to decompose, especially if it is stabilized and bound to clay (Hassink and Whitmore 1997; Sanchez 1997). Thus, the mineral soil may be a relatively static pool of carbon with inputs from fine root decay or root exudates nearly equivalent to decomposition losses as CO_2 with only a small residual fraction potentially accumulating in the soil. An exception follows logging, when there can be a major input of soil organic matter as severed root systems, forest floor, and logging slash are incorporated into the mineral soil. In addition, mineral soil carbon has been shown to increase following the conversion from agriculture to pine plantations (Lee and Dodson 1996). The balance of post-harvest inputs and decomposition of roots and forest litter overlaid on the gradually increasing regrowth of forest biomass makes the mineral soil a dynamic and difficult system to evaluate.

Productivity

Intensive forest management (i.e., weed control, fertilization, and genetics) can increase net ecosystem productivity (NEP) and forest carbon sequestration largely through increases in net primary productivity (NPP). Maier and Kress (2000) assessed the impact of fertilization on NEP in midrotation loblolly pine stands. Fertilization greatly increased total NPP and plant respiration, but had little effect on soil CO_2 evolution. Net ecosystem productivity was calculated in a component analysis *(table 1)* as the difference in total carbon used for plant production and total carbon lost in plant and heterotrophic (soil organisms) respiration. *Figure 3* shows nonfertilized stand NEP was slightly negative, indicating that at age 11 these stands were still a net source of carbon to the atmosphere (historically, the Southeast Tree Research and Education Site [SETRES] was a longleaf pine site on a deep, sandy soil). In contrast, the positive NEP of the fertilized stands indicates these stands were strong carbon sinks. The large difference in NEP between nonfertilized and fertilized stands was essentially due to increased pine productivity.

Fertilization response at SETRES has been particularly dramatic, as SETRES is a very nutrient-poor site and fertilization has been conducted to achieve "optimum" nutrition (Albaugh

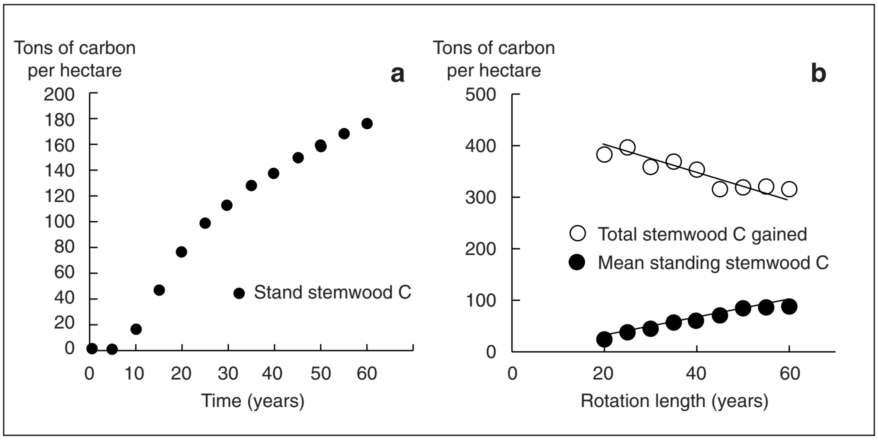

Figure 4. **(a) Modeled carbon accretion (stemwood only) over time for an upper Coastal Plain loblolly pine stand with a site index of 80, and (b) total carbon gained and mean standing carbon as a function of rotation length, both calculated over a 100-year period.**

et al. 1998). However, operational applications of fertilizer have been shown to consistently increase productivity across a large range in southern pine sites (Schultz 1997). In response, industrial fertilization increased from 40,000 acres per year in 1988 to 850,000 acres in 1998. Although southern pine stands typically are nutrient-limited, fertilization will need to proceed carefully so additions can be made in an environmentally acceptable manner. The matching of fertilizer supply with efficient plant use over the course of a rotation (i.e., stand nutrition management) will be required to optimize productivity while minimizing nutrient losses from forest stands. In addition, although it appears that fertilization can increase NEP via increases in NPP that increase standing biomass and soil organic matter, the overall impact of other practices associated with intensive forestry need to be assessed. For example, bedding increasingly is being used on seasonally wet sites and its long-term impact on soil carbon is not known.

Increased atmospheric CO_2 concentrations also likely will increase loblolly pine productivity (Groninger et al. 1999). In an 11-year-old stand subjected to Free Air Carbon Enrichment (FACE) technology at the Duke Forest, increases in growth due to elevated CO_2 during the first three years of enrichment averaged 34 percent; this increased growth dropped to 7 percent in the second three-year period (Oren 2000, unpublished data). Such initial, but not prolonged, sharp productivity increases were hypothesized by Groninger et al. (1999) and likely are due to site nutrient limitations. In studies conducted at the Duke FACE site (moderate fertility) and at SETRES (low fertility), the combination of fertilization and elevated CO_2 increased growth two and three times more than did the addition of elevated CO_2 and fertilization as separate treatments (Oren et al. 2000, unpublished data). Thus, productivity gains via fertilization may well increase as atmospheric CO_2 increases.

Silviculture Systems

In plantation forestry, rotation length will greatly influence the *in situ* forest carbon pools. *Figure 4a* shows a hypothetical time course of aboveground carbon accrual for an upper Coastal Plain loblolly pine plantation with a site index of 80. The growth curve was derived using the North Carolina State University Plantation Management Simulator. Using this growth curve, we plotted the impact of rotation age on the 100-year average *in situ* carbon pool and the total aboveground carbon absorbed (both harvested and standing carbon at the end of 100 years). While increasing rotation length does increase the mean standing *in situ* carbon pool, shorter rotations result in a greater amount of total carbon converted to wood products over the 100-year period *(fig. 4b)*. The latter result is due to the shorter rotation stands being harvested as productivity begins to decline, while the longer rotation maintains relatively slow growth rates for a longer proportion of the stand's lifespan. The conversion of this harvested carbon into products is also an important avenue of sequestration.

Not all southern pine forests are managed as even-aged stands. Uneven-aged forestry is particularly alluring where aesthetics are of paramount concern. For instance, in the Ouachita National Forest in Arkansas, approximately 3.2 million cubic feet of pine was harvested in both 1998 and 1999 entirely from uneven-aged stands (Guldin 2000, pers. commun.). Uneven-aged management can result in high and stable quantities of above- and below-ground standing biomass. Also, due to minimal ground disturbance, partial cutting will maintain a thick forest floor, potentially elevating mineral soil carbon concentration over the long term.

Ex Situ Carbon Pools

In managed southern pine forests, the absolute amount of carbon sequestered from the atmosphere depends largely on the fate of the harvested wood (Skog and Nicholson 1998). Different products—such as building materials, paper products, and fuel—have very different duration-of-use and final dispositions. The half-lives of a single-family home built after 1980, apartment buildings, and commercial buildings have been estimated to be 100, 70, and 67 years, respectively. Paper products have a short half-life of one to six years. Before 1972, most paper and waste wood products were burned in dumps. Landfills have now replaced dumps and the carbon in landfills is buried and available oxygen is consumed rapidly, resulting in low decomposition rates. This means that little decay of solid wood occurs; newsprint and kraft paper with 20 to 27 percent lignin content are also resistant to decay. It has been estimated that of the wood and paper that enters a landfill, the decay of solid wood is 3 percent, newsprint 16 percent, boxboard 32 percent, and office paper 38 percent, over a 50-year period (Micales and Skog 1997).

The final aspect of harvested wood is that burned for fuel. Waste wood is a common fuel in wood manufacturing plants, pulp mills, and paper processing plants. This fact is an important component of mitigation, because it is a direct replacement for fossil fuel use. In some forest management scenarios, replacement of fossil fuels with wood-burning can provide as much as 560 tons per acre in reduced carbon emissions from fossil fuels over a 50-year period, if all of the harvested wood is used for fuel (Schlamadinger and Marland 1996). In most cases, only waste wood and sawdust is burned, but this accounts for 45 tons of carbon per year in the United States (Row and Phelps 1996) in comparison to the 15 to 27 tons of carbon in wood and paper added annually to landfills (Skog and Nicholson 1998).

In Situ and *Ex Situ* Integration

An example of the potential importance of carbon sequestered both *in situ* and *ex situ* is shown in *figure 5.* These values are from simulations using the HARVCARB model for a generic loblolly pine stand in the southeastern United States (Row and Phelps 1996). This example assumes average rates of stand growth, a 25-year rotation, and products of lumber and pulp for paper production with waste burned for fuel. The output is in metric tons of carbon (1.102 short tons per metric ton) accumulated after four successive rotations. In this scenario, 25 years after the first harvest, 30 percent of the carbon from the first rotation remained stored in products. Over successive rotations the pool of carbon stored in products increases. An additional accumulation occurs in waste that enters landfills. Over time the carbon accumulation in these two pools of products and landfill waste, along with any buildup of *in situ* mineral soil carbon, indicates that successively harvested pine plantations *(fig. 5a)* have the potential to sequester significantly more carbon than uncultivated, unharvested forests *(fig. 5b).* When pine plantations are intensively managed to increase productivity using fertilization and weed control, the impact on carbon sequestration may be substantially magnified *(fig. 5c).* Although these analyses are informative, they use many gross approximations; more accurate analyses will require better quantification of model components.

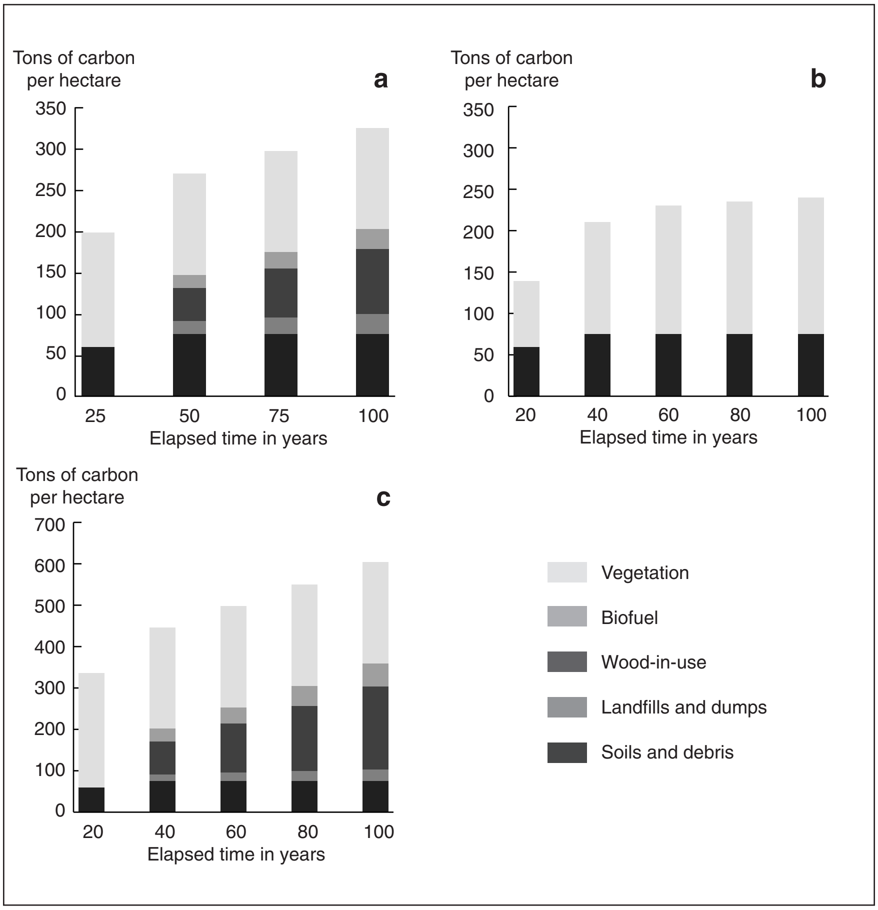

***Figure 5.* Integrated analysis of carbon sequestration using the model HARVCARB (from Row and Phelps 1996): (a) stand with site index of 75 and a 25-year rotation length; (b) an uncultivated, unharvested stand; and (c) stand managed to decrease rotation length to 20 years.**

Management Options, Research Needs

The absolute carbon sequestered and the balance between *in situ* and *ex situ* carbon sequestration of southern pine forests will be determined by the biology of forest growth and the economics that influence both land ownership patterns and investments in intensive forestry. There are also opportunities, however, for policy to affect the amount of carbon sequestered. One policy approach would be to provide incentives for converting marginal agricultural land to forestry. Besides increasing the standing aboveground carbon pool present in pine trees, and increasing the flow of carbon into *ex situ* pools of products, these marginal crop lands, where soil has often been degraded by cycles of agricultural tillage, may increase in mineral soil carbon when converted to pine. It has been estimated that there are 16 million acres of marginal farmlands in the southeastern United States (USDA-FS 1988). A small portion of this land, just 1 million acres, has been placed in pine plantations through the USDA Conservation Reserve Program; an additional 15 million acres could still be converted under economically profitable conditions for farmers (Plantinga 1997). Tax incentives, as a type of carbon credit, could be used to facilitate this goal. These sites likely will not be intensively managed and so will have moderate growth rates resulting in longer rotation ages, and thus higher *in situ* carbon sequestration. These stands may be of particular utility in decreasing near-term (next 35 years) net emissions while improvements in energy technologies hopefully decrease the reliance on fossil fuel, thus decreasing gross carbon emissions.

Again, intensive forestry may also increase carbon sequestration. The increased use of fertilization, in an environmentally acceptable fashion, will likely be a key component of increasing yields. Genetic improvement, spurred by advanced breeding, clonal forestry, and biotechnology will continue to heighten productivity, especially when elite genotypes are planted on intensively managed sites. The continued investment of forest industry will undoubtedly further increase productivity on their landholdings.

We foresee clear opportunities to increase the productivity of southern pine forests with the potential of augmenting carbon sequestration over the medium and long term. Such carbon sequestration gains, however, will require a careful management of intensifying forestry practices and an improved understanding of the *in situ* and *ex situ* factors controlling carbon storage. Strong support for research is needed on several fronts to better quantify the role of southern pine forestry in sequestering carbon, develop management strategies to increase carbon sequestration, and ensure that the forest management applied is sustainable over time.

More specifically, our understanding of below-ground carbon cycling is the weakest link in the *in situ* carbon chain. We need to reliably elucidate the controls of the major below-ground carbon pools. Long-term carbon dynamics will require the study of a well-organized network of long-term research sites. In intensive forestry operations, where sites are disturbed more frequently, we need to devise methods to minimize carbon losses following harvest. An example might be to modify the operational movement of slash and bark during harvest, perhaps even incorporating it below ground (Sanchez and Eaton 2001). Net ecosystem productivity (NEP) needs to be assessed on more site types representing more ages. The goal should be to integrate results from divergent studies into process models, eventually devising models that can be run using remotely sensed data.

Of course, estimates and predictions can only be fully scaled up if we have tools to accurately quantify current and future land-use patterns. Research to increase productivity via fertilization needs to establish optimum doses and frequencies of application so that environmentally acceptable nutrition management can be applied over the entire course of a rotation. Forest genetics and silviculture research need to work in concert so that the genetic–environmental system can be optimized. Research on the impacts of multiple rotations on long-term site sustainability will be paramount as our reliance on intensive forestry increases. However, as all sites will not receive intensive management, research on "extensive" silviculture, using longer rotation ages, or uneven-aged forestry, to produce high-quality, long-lifespan products needs to continue. These areas of research will help us realize the full potential of southern pine forestry to further decrease net US carbon emissions.

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