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How to Estimate Carbon Sequestration on Small Forest Tracts

International climate change agreements may allow carbon stored as a result of afforestation and reforestation to be used to offset CO_2 emissions. Monitoring the carbon sequestered or released through forest management activities thus becomes important. Estimating forest carbon storage is feasible even for nonindustrial private forestland (NIPF) owners, and the necessary tools are available. We developed a methodology for estimating forest carbon storage at the management unit scale and tested the impacts of hypothetical management scenarios on carbon sequestration over time. We demonstrate the procedure on two military installations in the southeastern United States and discuss some practical considerations.

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The Kyoto Protocol calls for each country that ratifies the agreement to reduce greenhouse gas emissions by specified targets below a 1990 baseline level during the first commitment period, 2008 to 2012. The target for the United States is a 7 percent reduction. Several provisions of the Kyoto agreement may affect how forestry is practiced in this country. For instance, Article 3.3 allows the use of selected carbon sinks to meet emission reduction targets. Verifiable changes in carbon storage from afforestation, reforestation, and deforestation since 1990 can be counted as credits or debits if they result directly from human activities. Article 3.4 provides an opportunity for countries to propose additional forest management activities. Other articles establish mechanisms for trading carbon credits among parties to the protocol and for assuring that credits are from projects that increase carbon sequestration above a baseline estimate. Terminology and accounting procedures were not well defined in the protocol, and international negotiations are under way to clarify how the agreement will be implemented if it is ratified by enough countries to become international law.

Although the Kyoto Protocol is an international agreement, the carbon consequences of forest management have implications for individual landowners and forestry professionals. Carbon stocks would have increased value, and landowners who could document increased carbon storage from management actions could take advantage of the opportunity to sell carbon credits. For example, a power plant in one state could purchase credit for stored carbon—"carbon credits"—from a landowner in another state to offset emissions from its operations.

To some extent, a market for carbon credits already exists in the United States, and several forestry projects designed to offset carbon emissions are under way (Fletcher and Gorte 1998). For example, a group of US electric

Above: **A study plot at the Coweeta Hydrologic Laboratory, Otto, North Carolina. Litterfall collectors are visible at the bottom of the photo.**

utilities has formed the UtiliTree Carbon Company, which has initiated carbon offset projects in several states. An Internet search on *carbon sequestration* or *carbon credits* pulls up many Web pages, including those for consulting companies in the business of managing and "selling" sequestered carbon.

Documenting current carbon stocks and expected changes establishes a baseline against which to demonstrate possible increased carbon sequestration through forest management; it also provides an opportunity to benefit from the transfer of carbon credits. As pressure increases to meet national emission reduction targets, the per-ton value of sequestered carbon will also increase. In addition, carbon storage is a criterion in international forestry sustainability agreements (Gluck 1996). At this time, it is both possible and practical to integrate carbon sequestration analysis into forest planning at the local level.

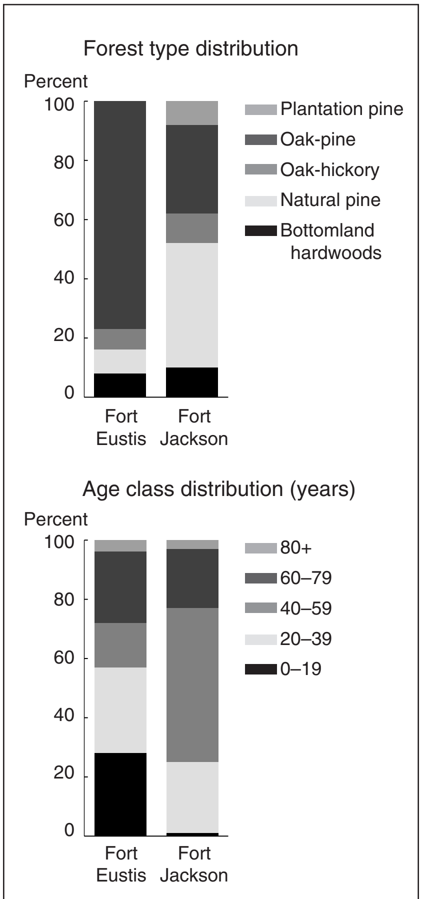

Figure 1. **Forest type and age class distribution of the forests of Forts Eustis and Jackson.**

In this study we describe a method for estimating carbon budgets for selected forest stands managed by the US Department of Defense, discuss the effects of six hypothetical forest management scenarios on carbon sequestration over an extended planning period, and demonstrate the use of this methodology.

Methodology

The military installations in the Southeast used in this analysis are Fort Jackson, South Carolina, with about 38,300 forested acres, and Fort Eustis, Virginia, with roughly 2,780 forested acres. They were chosen to illustrate the applicability of the method because they differ greatly both in size and in forest type and age class distributions *(fig. 1).* Both installations also have active forest management programs. The large proportion of oak-pine forest at Fort Eustis is a result of inventory methods that combined several stands into larger inventory units. This approach masked pine plantations and small natural stands, and affected age distributions. It results in a highly aggregated picture of forest composition but does not preclude developing estimates of carbon storage.

To construct a basic carbon budget, we converted volume estimates from a standard stand-level forest inventory to estimates of carbon. First, each stand was assigned a forest type based on stocking; "pure" stands had 80 percent of the basal area in a single type. The forest types used were broad to match the existing biomass-to-carbon conversion factors: natural pine, plantation pine, oak-hickory, oak-pine, and bottomland hardwood. For each forest type, the cubic-foot volume of timber in hardwoods and softwoods was summed from the inventory data. Because this estimate includes only merchantable volume, a conversion factor was applied to scale up to total above- and below-ground volume (total volume). The ratios of total to merchantable volume in *table 1* were derived from national estimates of biomass by tree section (Cost et al. 1990). This total cubic-foot volume of hardwoods and softwoods for each forest type was then converted to pounds of carbon using the regionally appropriate set of conversion factors *(table 2).* The entire volume-to-carbon conversion process, including the derivation of the conversion factors, is detailed in Birdsey (1992, 1996).

Table 1. Ratio of total volume (above- and below-ground tree biomass) to merchantable volume for hardwoods and softwoods, by region.

Region	Hardwood	Softwood
Southeast	2.233	1.682
South Central	2.869	1.786
Northeast	2.140	2.193
Mid-Atlantic	2.140	2.193
North Central	2.418	2.514
Central	2.651	2.601
Rocky Mountain	2.214	2.254
Pacific Coast	2.279	1.675

Source: Birdsey (1992)

To assess the effects of various management actions on carbon storage, two regionally appropriate stand-level growth-and-yield models were used: WINYIELD (FORS Institute 1997) and NATYLD (Smith and Hafley 1987; Smith et al. 1989). Six hypothetical management scenarios, chosen to test a range of management intensities, were then modeled *(table 3).* The rotation ages used are longer than typical for the Southeast and were chosen to maximize the amount of biomass without substantially decreasing economic returns. In all scenarios, no natural pine 65 years or older at the start of the simulation period was cut, and bottomland hardwood stands were left to grow without management. In the oak-hickory and pine sawtimber scenario, no oak-hickory over age 85 at the start of the simulation period was cut. This was done to retain older age classes in the simulated forest. Any appropriate growth-and-yield model can be used to evaluate management actions, though the management options that can be evaluated depend on the features of the particular model chosen. Well-validated growth-and-yield models may not be available for certain timber types, such as fast-growing willows or hybrid poplars. Mixed-species models can also be difficult to find. The models selected should be appropriate to the geographic region and forest type.

Table 2. Factors to convert tree volume (cubic feet) to carbon (pounds) for regional forest types and plantation species.

Region	Forest type	Conversion factor		Plantation species	Factor
		Hardwood	Softwood		
Southeast and South Central	Pines	19.82	16.90	Loblolly, shortleaf pine	15.57
	Oak-hickory	19.82	17.76	Slash pine	17.89
	Oak-pine	19.82	17.33	Longleaf, slash pine	17.89
	Bottomland hardwoods	17.99	15.24		
Northeast and Mid-Atlantic	Pines	16.87	12.29	White, Norway spruce	12.03
	Spruce-fir	16.31	12.00	Loblolly pine	15.28
	Oak-hickory	19.76	12.16	Black spruce	12.35
	Maple-beech-birch	18.65	12.48	Red pine	13.33
	Bottomland hardwoods	17.99	14.96	Hardwoods	18.96
North Central and Central	Pines	16.47	13.69	Red pine	13.33
	Spruce-fir	14.92	11.41	White, Norway spruce	12.03
	Oak-hickory	19.64	13.52	White pine	11.05
	Maple-beech	17.90	12.09	Hardwoods	18.96
	Aspen-birch	14.45	12.03	Black walnut	15.85
	Bottomland hardwoods	17.99	14.96	Colorado blue spruce	12.03
				Ash	17.09
Rocky Mountain and Pacific Coast	Douglas-fir	11.76	15.11	Ponderosa pine	12.14
	Ponderosa pine	11.76	13.29	Douglas-fir	14.38
	Fir-spruce	10.67	9.80		
	Hemlock-Sitka spruce	12.16	12.17		
	Lodgepole pine	10.67	11.86		
	Larch	12.16	14.26		
	Redwoods	16.29	11.68		
	Hardwoods	10.77	11.90		

Source: Birdsey (1992)

Stand data obtained from installation inventories were entered into the model and stands were grown for 50 years using each hypothetical scenario. Yields were reported every 10 years and were converted to carbon as described earlier. The utilized volume of harvested trees was counted as sequestered carbon because the carbon is transferred to products. Sawtimber and pulpwood products have different lifetimes, so we tracked harvested pulpwood and sawtimber carbon through time (to products, landfills, etc.) using tables derived from the HARVCARB model of Row and Phelps (1996), as given in Birdsey (1996).

In addition to biomass, we also estimated the coarse woody debris, litter, and soil carbon components of an ecosystem carbon budget. We adjusted regional estimates from Birdsey (1996) according to stand age and the assumptions used in the national carbon budget (Heath and Smith, in press): 50 percent litter loss and 20 percent soil carbon loss from harvest if followed by intense site preparation; otherwise, no loss of soil carbon (for regions other than the Southeast, soil carbon loss after harvest is assumed to be 0). Soil carbon trends depend greatly on previous land-use history, so we asked the Fort Jackson and Fort Eustis foresters about land-use history and learned that most of the land had not been cultivated since the 1940s. Because biomass dominates carbon accumulation, if a history of previous land use is lacking, the landowner can focus on the biomass portion of the carbon

Table 3. Simulated hypothetical management scenarios representing a range of management intensities.

Scenario	Action modeled
Growth only	No management; continued growth only.
Pine sawtimber	No thinning. Pine stands harvested at 55 or 65 years depending on volume. Replanted to previous species at 750 trees per acre. Longleaf pine replanted to 650 trees per acre.
Pine sawtimber, oak-pine conversion	Same as above; in addition, all oak-pine stands are harvested in 2005 and replanted to equal acreages of appropriate pine species.
Pine pulpwood	No thinning. Pine stands harvested at 25 or 35 years depending on volume. Replanted as in pine sawtimber scenario.
Pine sawtimber, oak-hickory sawtimber	Pine sawtimber as above. Oak-hickory sawtimber harvested at 85 or 95 years depending on volume. No thinning.
Pine sawtimber with single thinning	Pine sawtimber as above with single thinning at a variable age, depending on volume.

Step-by-Step Carbon Accounting

Although estimating carbon sequestration for a forested tract may seem complicated, the tools are already at hand. The basic steps follow.

1. Inventory standing timber volume, by forest type, using standard methods.

2. Convert merchantable volume (cubic feet) to total volume (above- and below-ground) using appropriate conversion factors *(table 1)*.

3. Convert total volume to pounds of carbon using regional forest type factors *(table 2)*.

4. Estimate coarse woody debris, litter, and soil carbon based on region and stand age using methods such as outlined in Birdsey (1992). Soil can be ignored as a sink except when former agricultural lands are reforested (see text for explanation).

5. Add the results of steps 3 and 4 to find the current carbon storage.

6. Estimate losses of litter and soil carbon from harvest and site prep as 50 percent litter carbon loss, 20 percent soil carbon loss for Southeast, 0 percent loss elsewhere in the United States (Birdsey 1996; Heath and Smith, in press).

7. Assume that harvested carbon is sequestered in products, and use life-cycle estimates from HARVCARB model (as given in Birdsey 1996) to account for harvested material.

8. Use a growth-and-yield model with inventory data and assumptions in steps 6 and 7 to estimate the carbon impacts of various management strategies.

9. Compare the results of step 8 with the estimate of current carbon storage from step 5.

Table 4. Carbon stocks at Forts Eustis and Jackson, in tons (English) of carbon per acre and tons of carbon over the entire forested acreage. These values represent carbon storage as of 1995 for all forest stands on the installations.

	Fort Eustis		Fort Jackson	
	Tons of carbon per acre	Total tons of carbon	Tons of carbon per acre	Total tons of carbon
Soil	31	87,540	33	1,249,794
Litter	2	6,909	4	145,971
Trees	39	109,301	24	926,897
Total	72	203,750	61	2,322,662

budget to estimate carbon sequestration resulting from management activities.

Estimates of carbon stocks for 1995 *(table 4)* were calculated from installation inventory data as previously described. *Table 4* gives the carbon stocks for Forts Eustis and Jackson; the effect of installation size is obvious from the values for total tons of carbon. If the same results are displayed as per-acre values, direct comparisons can be made. Fort Eustis, though much smaller, has a higher level of carbon storage per acre because of its larger biomass component, which is a result of several factors, including a higher stocking level. Results can also be displayed as per-acre values for each forest type and age class, to compare the carbon storage potential of various stands.

Management Options

The effect of simulated management scenarios for the years 2015 (shortly after the end of the first Kyoto commitment period) and 2045 are shown in *figure 2.* Two points are obvious: short- and long-term results may be different for a given scenario, and the results are strongly linked to the starting conditions of the stands being evaluated. For Fort Eustis, the conversion of oak-pine stands to pine plantations led to a large carbon gain by the end of the simulation period. Fort Eustis has a large oak-pine component, and replacing this with fully stocked pine plantations results in a carbon gain greater than that for any other scenario, including continued growth only. This scenario also “wins” for Fort Jackson, but the gain is not as large because the oak-pine type is a smaller component of its forest.

For both installations, harvesting pine sawtimber did not affect carbon storage; any differences from the continued growth baseline were minor. The sawtimber-with-thinning scenario also did not differ from the baseline, but the outcomes of other scenarios depended on initial age and forest type distributions. In general, any action that replaces understocked stands with fully stocked stands tends to increase carbon storage relative to the continued-growth baseline, as do management actions that increase standing volumes.

Another way to evaluate carbon consequences is with annual yields. The results from the management scenario simulations can be converted to average annual yields of carbon rather than timber. These are given in *table 5* (p. 18) for each scenario and provide an easy way to compare yields of carbon and timber. The two generally should be similar, though the highest carbon yields may require longer rotations or delayed returns on investment compared with the highest timber yields (Plantinga and Birdsey 1994). In *table 5,* some of the carbon yields are higher than the timber yields for a given scenario because the carbon in products and landfills was tracked over time, but the volume of harvested timber was counted at the time of harvest. The difference is greater for Fort Eustis, where products from the large oak-pine harvest are carried through the planning period. Operationally, a harvest of that size would not occur at a single point in time. Management strategies that yield the highest average annual yields of carbon generally do not conflict with those that produce the highest timber yields; however, individual results depend on initial stand conditions. The calculation of average annual carbon yields facilitates the use of carbon budgets as a planning tool.

Current Assumptions

Constructing the above-ground biomass portion of a carbon budget is straightforward. Much work has been done on methods to estimate standing volumes and biomass of timber, including nonmerchantable portions. The carbon content of various types of wood is known, well-validated growth-and-yield models are available, and the fate of harvested carbon in products continues to be investigated (Skog and Nicholson 1998).

Knowledge of litter and soil carbon stocks and dynamics, however, is not so advanced. Estimates of soil and litter carbon are problematic, the effects of management activities on soil and litter carbon are not well understood, and standing stocks of forest soil carbon are rarely measured. A review of the effects of forest management on soil carbon (Johnson 1992) revealed that harvesting results in slight positive or negative changes (usually 10 percent or less) with subsequent rapid recovery to preharvest levels. This finding is based on a small number of studies conducted with different methods. There has been little research on the effects of fire, and outcomes vary with vegetation type and fire severity (Blackwell et al. 1995; Fernandez et al. 1997). Treatments such as thinnings, shelterwood cuts, fertilization, and liming have received little attention.

To monitor carbon storage on a tract of forest, a landowner may wish to assume no substantial effects on soil carbon and consider only the tree biomass carbon. This would simplify the accounting process while providing a verifiable estimate of carbon storage, and the estimates produced can be used as a baseline against which to measure future change. An exception would be in the case of establishing plantations on former agricultural land that has been under cultivation for some time. In this situation, substantial amounts of carbon may accumulate in the soil and should be accounted for as previously described (Post and Kwon 2000).

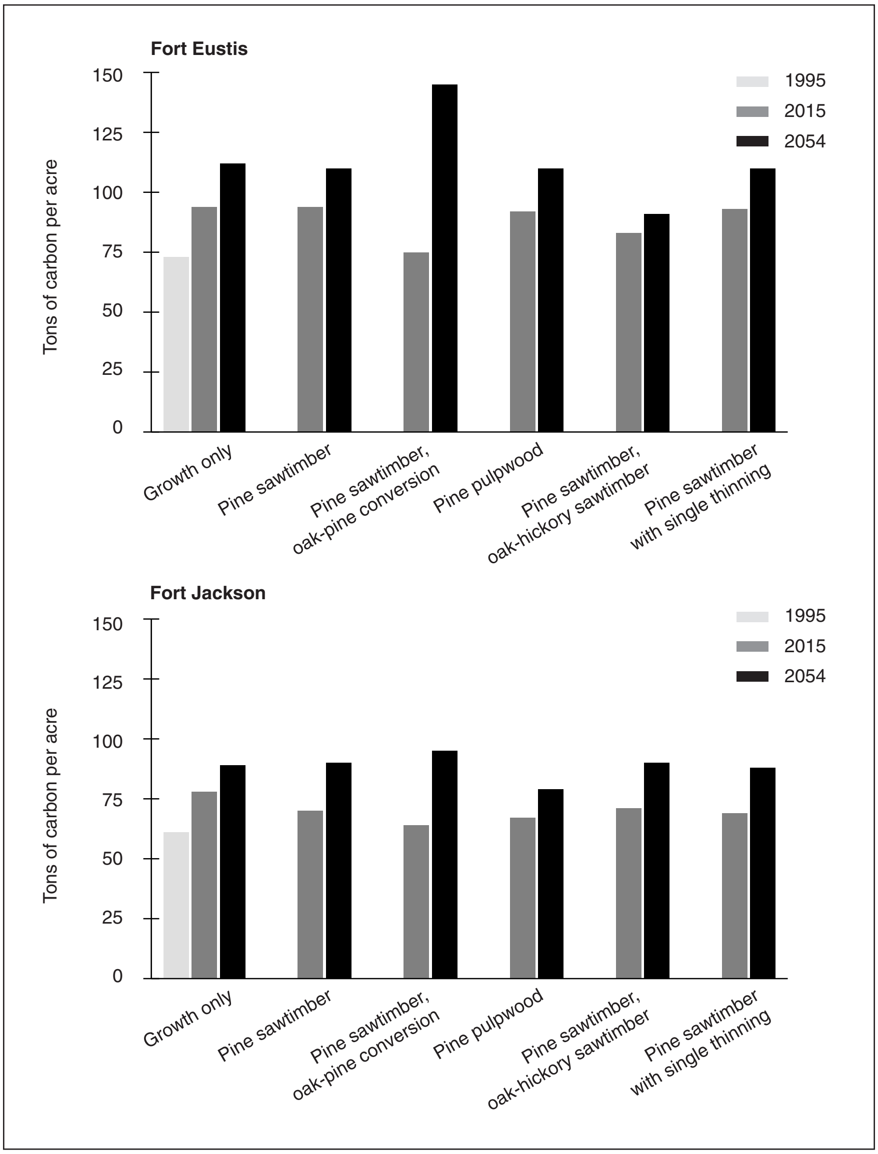

Figure 2. **Results of simulated management scenarios for Forts Eustis and Jackson. Results are in English tons and reflect growth of all forest stands.**

In our study, soil carbon was estimated on the basis of regressions developed by Birdsey (1992) from the data of Post et al. (1982), and a set of assumptions about the effects of harvesting and reforestation on soil carbon dynamics. Litter carbon was estimated with data from previous studies. Whole-tree utilization was assumed and the harvested volume was transferred to the product pool using the HARVCARB model of Row and Phelps (1996). Logging residues were assumed to be minor and were excluded from the analysis.

Harvested carbon can be allocated with varying degrees of precision; our assumption of whole-tree harvest was chosen to simplify the procedure. If bole-only harvest was to be modeled, the merchantable and total volumes would be computed, the merchantable volume transferred to the product pool, and the unmerchantable portion (the difference between the two estimates) left to decompose. Counting the entire harvested merchantable volume as sequestered will alter the estimate of sequestered carbon; however, the difference is small relative to the carbon budget for the entire forest. We

For More Information on the Kyoto Protocol

Details on the Kyoto Protocol, the United Nations Framework Convention on Climate Change, and the negotiation process are available on the following websites:

- UN Framework Convention on Climate Change: www.unfccc.int
- Intergovernmental Panel on Climate Change: www.ipcc.ch. This website contains the *Summary for Policymakers of the Land Use, Land Use Change, and Forestry Special Report,* which describes the issues under negotiation.

Table 5. Average annual yields of carbon (English tons) and merchantable timber for each simulated management scenario (values are for the forested acreage of each installation and are not adjusted for area).

	Fort Eustis		Fort Jackson	
Scenario	Tons of carbon per year	Cubic feet of timber per year (thousands)	Tons of carbon per year	Cubic feet of timber per year (thousands)
Growth only	2,140	63	21,888	1,507
Pine sawtimber	2,046	54	22,777	1,466
Pine sawtimber, oak-pine conversion	3,978	62	26,536	2,028
Pine pulpwood	2,055	57	13,936	331
Pine sawtimber, oak-hickory sawtimber	1,010	53	22,824	1,204
Pine sawtimber with single thinning	2,074	57	20,950	888

found that even with fairly high harvest levels, there were only minor differences between estimates of carbon stock using a single allocation of harvested material to the sequestered pool or changing allocation (to products, landfills, energy, or emissions) through the planning period.

Whether carbon in harvested wood and products can be counted as sequestered under the Kyoto Protocol is one of the points under international negotiation. Once wood products are in trade, it may be difficult to determine to whom credit should be assigned.

Factors that Affect Estimates

Estimates of carbon stocks reflect several factors, including stocking level, age class distribution, and site productivity. Well-stocked stands will store more carbon per acre, so any management scenario that increases stocking levels also increases carbon sequestration. Older stands have high per-acre carbon storage, but the rate of accumulation is slow and can be negative if a stand is senescent. Very young stands have low per-acre storage but rapid accumulation rates. Hardwoods have lower growth rates but higher carbon density than pines. In all the hypothetical scenarios, regeneration was prompt and harvesting generally did not result in a decrease in carbon storage. Failure to establish and maintain adequate regeneration promptly after harvest can result in a loss of stored carbon, because biomass, soil, and litter pools are affected. Many factors need to be considered when evaluating the carbon consequences of potential management options; the end result often depends on initial stand conditions. Age and composition of the forest affect more than the biomass estimates; because litter and soil carbon are estimated based on age, the higher litter and soil carbon storage at Fort Jackson reflects the relatively few acres in the youngest age class.

The large differences between short- and long-term results also need to be considered: An action that results in a large carbon gain in the long term may be a poor choice if short-term results are desired. Although the oak-pine conversion scenario is unrealistic, it yields a substantial long-term gain. However, if results were counted at the end of the first Kyoto commitment period (2012), virtually no carbon would have accumulated. Although forests can provide a carbon sink, any substantial gains (even with fast-growing plantation species) will take time.

As with any management objective, maximization of carbon sequestration must be balanced with other values. In many cases, practices mentioned above, such as maintaining stocking and ensuring prompt regeneration, are considered good forestry and are compatible with a wide variety of other objectives. Other possible methods of increasing sequestration, such as lengthening rotations, may be consonant with landscape diversity or wildlife management values. Actions such as large-scale conversions (like the oak-pine conversion simulated here) may sequester large amounts of carbon but be unacceptable from an ecosystem management perspective. On the other hand, replacement of exotics with native species could potentially increase carbon storage. Careful consideration of possible tradeoffs is always necessary when choosing a management strategy; now carbon sequestration can be included in the list of management objectives for forest landowners.

Developing a reliable estimate of forest ecosystem carbon requires a thorough forest inventory. Accuracy of carbon estimates depends on the accuracy of the timber cruise and the estimation procedures. Collecting data on soils and detritus would improve accuracy but is not necessary for basic estimates of changes in carbon storage in the absence of severe ground disturbance. The essential data are timber volumes for both hardwood and softwood, pulpwood and sawtimber, by broad forest type.

If scenario modeling is desired, any regionally appropriate growth-and-yield model can be used. The primary model used in this analysis is commercially available and geared toward landowners. The data required for scenario simulation depend on the model selected; in this analysis, the necessary variables were stand size, stand age, trees per acre (plantations), basal area (natural stands), and site index. A stand table would have provided better model calibration but was not required. Again, the data requirements and flexibility of scenario simulation options are determined by the growth-and-yield model chosen. If growth-and-yield projections already are modeled and used in planning, the same model can be used to estimate carbon yields under planned management actions.

Conclusion

Estimating forest carbon storage is feasible even for small landowners, and the necessary tools are readily available. Although individual landowner reporting of carbon storage on forested land is not required at this time, calculating current carbon stocks will document a starting point against which to measure carbon sequestration. Integrating carbon sequestration objectives into planning allows managers to assess compliance with sustainability criteria, as well as the opportunity to take advantage of carbon credit trading, which can become yet another recognized value of well-managed forestlands.

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