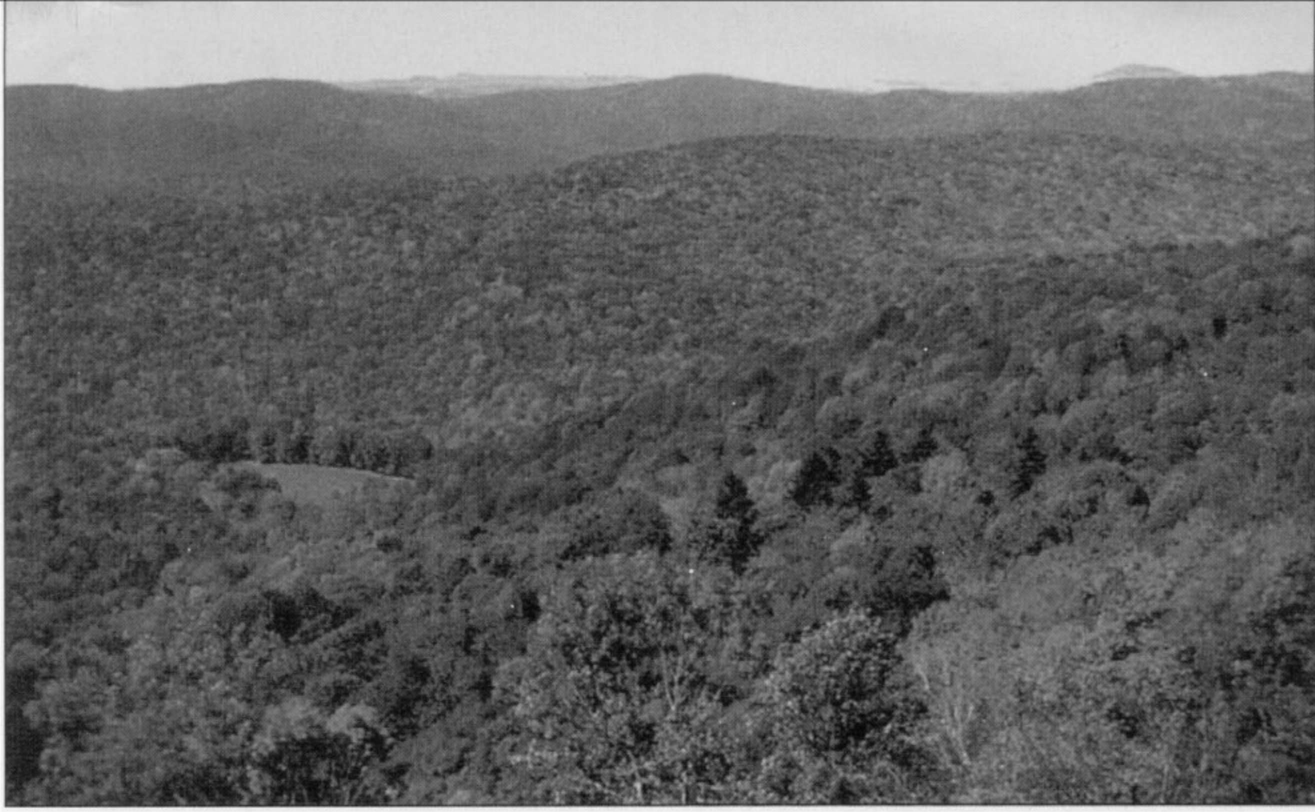

How to Estimate Forest Carbon for Large Areas from Inventory Data

James E. Smith, Linda S. Heath, and Peter B. Woodbury

ABSTRACT

Carbon sequestration through forest growth provides a low-cost approach for meeting state and national goals to reduce net accumulations of atmospheric carbon dioxide. Total forest ecosystem carbon stocks include "pools" in live trees, standing dead trees, understory vegetation, down dead wood, forest floor, and soil. Determining the level of carbon stocks in forest ecosystems has become a concern of governments, businesses, and many organizations. This article provides examples of inventory-based calculations and identifies resources that are available for analysts and planners to develop large-scale carbon estimates consistent with totals for US forests. Estimates can be based on current regional averages classified according to region, forest type, ownership, or stand size class; on stand-level inventory data, measured or calculated; or on locally specific information, such as individual tree sizes or other data acquired from sampling a specific forest.

Keywords: climate change; sequestration

Carbon sequestration is becoming an increasingly important component of the value of forests as natural resources. The link between possible climate change and the accumulation of greenhouse gases in the atmosphere is behind this value—forests remove carbon dioxide from the air and store this greenhouse gas in the form of organic carbon. Many countries have formed international agreements to document and reduce emissions of carbon dioxide and other greenhouse gases. In 1992, for example, 150 countries, including the United States, signed the United Nations Framework Convention on Climate Change. Such international discussions and agreements have resulted in the development of annual reports of US greenhouse gas inventories (US EPA 2003a, 2003b), which include carbon in forests. This interest has ex-

Above: **Carbon on the Monongahela National Forest, West Virginia.**

Metric Conversion Factors

1 hectare = 10,000 m^2 = 2.471 acres
1 m^3 = 35.31 ft^3
1 metric ton = 1,000 kg = 1,000,000 g = 1 Mg
1 metric ton = 1.102 US tons = 2,205 pounds
1 megatonne = 1,000,000 metric tons = 1 Mt

Examples:
100 m^3 per ha = ~1,429 ft^3 per acre
100 metric tons per ha = ~44.6 US tons per acre, or ~89,200 pounds per acre

tended to quantifying forest carbon for distinct areas within the United States, such as regions, states, counties, or even watersheds (USDA 2004a, 2004b; US EPA 2003a, 2003b).

This article demonstrates how forest ecosystem carbon budgets can be compiled quickly for forestlands of tens of thousands to millions of hectares based on readily available forest inventory data for the conterminous United States. Carbon estimates based on the extensive forest inventory of the USDA Forest Service Inventory and Analysis Program (FIA) can serve as representative values for specified forestlands. The inventory-to-carbon linkage is from national-scale forest carbon budgets developed by the USDA Forest Service (Heath et al. 2003; USDA 2004a, 2004b). These methods are principally intended for analysts or planners interested in quantifying carbon over extensive forestlands. However, the same inventory-based approach can be applied to develop carbon estimates for projects of smaller areas as well.

Carbon from Inventory

Inventory-based approaches to estimating forest carbon stocks generally use factors applied to inventory variables, such as timber volumes, to estimate carbon mass in trees. Empirical or simulation models are frequently used to develop estimators for separate carbon pools, such as living trees, dead wood, or soil (Birdsey 1996; Haswell 2000; Hoover et al. 2000). Estimators often are further classified according to forest type, region, and management regime. Haswell (2000) provides an overview of some considerations in developing factors to apply to inventory data from the Pacific Northwest. FIA inventory data have been the bases for a number of estimates of forest carbon stocks (Birdsey 1992; Birdsey and Heath 1995; Haswell 2000; Hoover et al. 2000; Martin et al. 2001; Brown 2002; Ney et al. 2002).

Carbon estimates provided here are from the forest carbon budget simulation model FORCARB2 (Birdsey and Heath 1995; Heath et al. 2003). This is an empirical simulation model that provides inventory-based estimates of US forest carbon stocks. Thus, carbon stocks reflect inventory changes associated with forest management, growth, mortality, harvest, and changes in land use. The model identifies the following separate components of total forest ecosystem carbon stocks: live trees, standing dead trees, understory vegetation, down dead wood, forest floor, and organic carbon in soil.

The approaches to estimating forest carbon that we describe can be broadly classified in three levels of increasing specificity, with correspondingly detailed inventory data:

- *Area-based carbon estimates* are from current regional averages classified according to region, forest type, ownership, or stand size class. Forestlands are assigned representative average values according to the classification data available.
- *Stand-level inventory* provides quantitative data—measured or calculated—that improve on the area-based estimates. Specifically, stand volume and age are input data that estimate tree and forest floor carbon, respectively.
- *Locally specific information,* such as individual tree sizes or other data acquired from sampling a specific forest, can replace the representative average values when available.

Three forest types are used as examples in the discussion below: hemlock–Sitka spruce forests in the Pacific Northwest, west side (Oregon and Washington west of the crest of the Cascade Mountains); aspen-birch forests in the northern Lake States (Michigan, Wisconsin, and Minnesota); and oak-pine forests in the Southeast (Florida, Georgia, South Carolina, North Carolina, and Virginia). Extensive tables of summary values or regression coefficients organized according to forest type and carbon pool are needed to extend the examples to other forests. These tables are available on the Internet at www.forestcarbon.net. English-to-metric conversion factors are provided (see sidebar) because all of our equations are in metric units. Thus, areas are in hectares, volumes are in m^3, and carbon mass is expressed as metric tons.

Area-Based Estimates

Area-based carbon stocks are developed by applying FORCARB2 to forest inventory data from the 2002 Renewable Resources Planning Act (RPA) database (http://ncrs2.fs.fed.us/4801/fiadb/index.htm). The use of this national database facilitates estimation of carbon even if information is very general, such as total area of a particular forest type. Carbon stocks are then determined by simply extracting the most appropriate summary. See Smith et al. (2001) and Miles et al. (2001) for summary information about US forest inventories and overviews of how forestlands are classified.

Carbon in live and standing dead trees. Inventory data, and thus average values for tree carbon, are most commonly available for timberlands—forests that meet minimum levels of productivity and available for timber harvest. *Table 1* provides regional average values for live tree carbon density (metric tons of carbon per hectare) on timberlands according to region, forest type, ownership (public versus private), and stand size class. Alternatively, *table 2* includes live and standing dead tree carbon density according to region, forest type, and ownership. Coarse roots of live and dead trees are included with the tree carbon pools. Tree carbon estimates include all trees with diameters at breast height (dbh) of at least 2.5 cm and are based on the 2002 RPA data and the regression equations in Smith et al. (2003).

Table 1. Estimates of carbon mass density in live trees based on forest type and stand size class data for timberlands.

Forest type[1]	Ownership	Stand size class[2]	Live tree	Live tree, aboveground
			metric tons of carbon per hectare	
Pacific Northwest, west side, hemlock–Sitka spruce	Public	Sapling	56.8	46.8
		Poletimber	74.2	61.1
		Sawtimber	218.2	180.0
	Private	Sapling	25.9	21.3
		Poletimber	68.0	56.0
		Sawtimber	162.6	134.1
Northern Lake States, aspen-birch	Public	Sapling	21.7	18.0
		Poletimber	63.9	53.4
		Sawtimber	73.4	61.4
	Private	Sapling	23.2	19.3
		Poletimber	61.7	51.6
		Sawtimber	72.7	60.8
Southeast, oak-pine	Public	Sapling	22.0	18.2
		Poletimber	60.0	50.0
		Sawtimber	86.6	72.3
	Private	Sapling	20.1	16.7
		Poletimber	55.9	46.5
		Sawtimber	85.4	71.2

[1] *For additional forest types, see www.forestcarbon.net.*
[2] *Timberlands are productive forests available for harvest of wood products, and stand size classifications on timberlands are based on the distribution of tree diameters in a stand.*

Table 2. Estimates of carbon mass density according to carbon pool, based on forest type.

Forest type[1]	Group[2]	Live trees[3]	Standing dead trees[3]	Understory	Down dead wood	Forest floor	Soil
			metric tons of carbon per hectare				
Pacific Northwest, west side, hemlock–Sitka spruce	Public	175.6	20.2	2.8	17.1	40.9	157.1
	Private	112.7	15.2	3.1	10.9	25.8	157.1
	Other	163.6	20.3	2.7	15.2	37.5	157.1
Northern Lake States, aspen-birch	Public	49.1	8.8	2.0	4.0	8.3	237.0
	Private	50.6	9.0	2.0	4.1	8.3	237.0
	Other	48.3	9.4	2.0	3.9	10.1	237.0
Southeast, oak-pine	Public	58.2	2.6	3.4	3.7	10.2	82.3
	Private	51.5	2.4	3.4	3.3	8.9	82.3
	Other	92.7	4.1	3.1	5.9	10.6	82.3

[1] *For additional forest types, see www.forestcarbon.net.*
[2] *Public and private timberlands, with reserved and low-productivity forests combined as "other."*
[3] *Tree carbon densities are for entire tree (above- and belowground).*

Carbon in understory vegetation. The understory carbon pool includes the aboveground biomass of all trees less than 2.5 cm dbh along with all nontree vegetation. Data on understory carbon are limited, but this is not a major problem because the understory contains only a small part of the total carbon in most forests in the conterminous United States. Estimates for average values for carbon in understory vegetation are presented in *table 2* as average tons of carbon per hectare according to region, forest type, and ownership. Values are based on estimates from Birdsey (1992, 1996) as applied to the 2002 RPA data.

Carbon in down dead wood. Down dead wood, or coarse woody debris, is the large woody material fallen or cut and left from live and standing dead trees with a diameter of at least 7.5 cm. Data on this carbon pool have not been collected on many plots, so information is currently limited. The amount of down dead wood is highly variable and depends on the history of land use, disturbance, and management at each site. Estimates in *table 2* represent averages from FORCARB2 simulations that include effects of growth, mortality, disturbance, and decay.

Carbon in the forest floor. Forest floor is defined as organic matter lying on the surface of the mineral soil, including small woody debris with a diameter up to 7.5 cm. As for the

Table 3. Coefficients for estimating stand-level tree biomass density based on growing stock volume, from Smith et al. (2003, table 3).

Forest type[1]	Scale correction	Coefficients[2]		
		F	G	H
		Entire tree		
Pacific Northwest, west side, hemlock–Sitka spruce	0.96	2,017	0.0196	2,968
Northern Lake States, aspen-birch	0.94	362	0.0524	270
Southeast, oak-pine	0.90	420	0.0353	310
		Aboveground only		
Pacific Northwest, west side, hemlock–Sitka spruce	0.96	1,670	0.0194	2,977
Northern Lake States, aspen-birch	0.94	304	0.0516	271
Southeast, oak-pine	0.90	353	0.0347	312

[1] *For additional forest types, see www.forestcarbon.net.*
[2] *Live tree biomass predictions based on the equation: Live tree biomass density (metric tons per hectare) = F × (G + (1 – exp(–volume/H))).*

Table 4. Coefficients for estimating carbon mass from volume of wood, based on average stand-level specific gravity of merchantable wood.

Forest type[1]	Volume to carbon mass conversion[2]
	metric tons of carbon per cubic meter
Pacific Northwest, west side, hemlock–Sitka spruce	0.2032
Northern Lake States, aspen-birch	0.1954
Southeast, oak-pine	0.2495

[1] *For additional forest types, see www.forestcarbon.net.*
[2] *Conversion coefficient = average specific gravity × weight of water × percentage of carbon.*
Source: Based on a compilation of specific gravities of wood according to species and tree records in the FIA database, fall 2002.

other carbon pools, average values were determined for forest floor carbon by applying the FORCARB2 estimators to the 2002 RPA data *(table 2)*. Forest floor carbon estimators are from Smith and Heath (2002).

Organic carbon in soil. The amount of organic carbon in soils is spatially variable, even within a relatively homogeneous forest, and consistent datasets covering large forested areas are few (Heath et al. 2002, 2003). We provide estimates of organic carbon in both mineral and organic soils (histosols) to a depth of 1 meter, but there is much uncertainty in these estimates. Fine roots of trees are included in the soil pool. Average soil organic carbon density estimates provided in *table 2* are assigned by forest type and are based on summary information in Johnson and Kern (2003).

Estimates from Stand-Level Inventories

To improve on the representative average approach described above, stand-level data from inventory can be used, if available. The volume of merchantable wood (hereafter referred to as "volume") is a calculated summary variable that can be expressed on a unit area basis, such as m^3 per hectare. In this form, volume serves as an input to live and standing dead tree carbon mass estimates in FORCARB2 (Smith et al. 2003). Similarly, stand age is an input to estimates of forest floor carbon (Smith and Heath 2002). If the appropriate inventory data are available, the equations discussed below can be used to improve carbon estimates for their respective pools.

Carbon in live trees, predicted from growing stock volume. The definition of growing stock used by FIA includes live trees of commercial species meeting specified standards of quality and size (12.7 cm dbh and larger, for example). Volume-to-biomass equations (Smith et al. 2003) use stand-level volume (m^3 per hectare) to estimate biomass (metric tons per hectare) of all trees greater than 2.5 cm dbh. Carbon mass in trees is approximately 50 percent of dry biomass (IPCC et al. 1997).

These volume-to-biomass equations include biomass expansion factors that account for all trees, including saplings and nonmerchantable trees. Estimates are made according to region and forest type and can include either total live tree biomass (both above and below ground) or just aboveground live tree biomass as a function of growing stock volume, as follows:

Live tree biomass density

$$= F \times (G + (1 - \exp(-\text{volume}/H)))$$

where the units for biomass density are metric tons per hectare dry weight; the units for volume are m^3 per hectare; and F, G, and H are coefficients, as shown in *table 3*.

▶ Example calculation for a northern Lake States aspen-birch forest with a growing stock volume of 120 m^3 per hectare, for above- and belowground stand-level mass density:

Live tree mass density (entire tree)
= 362 × (0.0524 + (1 – exp(–120/270)))
= 148.9 tons per hectare dry weight
Live tree carbon mass density
= 74.4 tons carbon per hectare

The volume-to-biomass equations are nonlinear, so mean carbon density from several samples across a large landscape of forests will be different from carbon density calculated from the mean volume over the large area. The amount of this difference, or bias, depends on how volume is distributed over the area of forest. Therefore, we recommend applying equations to plot-level volume data before summing over large areas, if such data are available. The stand-level tables can be applied to estimate carbon over large areas of forest without bias if the distribution of volume over the area is known. Carbon estimates can be made from that distribution of volumes rather than the single aggregate volume.

If only aggregated data are available, we provide simple linear corrections under the assumption that the distribution of volumes in the specified area is identical to that for the entire forest type across the region. Carbon density is multiplied by the correction factor to estimate carbon over a very large area. For example, if the volume of 120 m^3 per hectare in the above example represented an aggregate volume over 100,000 hectares rather than a single inventory plot, we would apply the correction factor:

Carbon in forest ecosystems can be divided into six "pools," each of which can vary greatly with the site and its management.

Live tree carbon
= 100,000 ha × 74.4 tons carbon per hectare × 0.94
= 6.99 million tons carbon

Using the uncorrected carbon value would overestimate total carbon by 6 percent.

When merchantable wood is harvested and processed, the proportion of ecosystem carbon that goes into wood products can be estimated by expressing volume of wood in terms of mass of carbon. This is based on the specific gravities of wood for species within the stand; examples of such conversion coefficients are shown in *table 4*. For example, if the above calculations were repeated for a single stand of hemlock–Sitka spruce forests in the Pacific Northwest, west side, with a volume of 800 m^3 per hectare, carbon density would be 258 tons per hectare. The percentage of carbon in live trees that is in merchantable wood is estimated as follows:

Percent carbon in merchantable wood
= Volume (m^3/ha) × coefficient (tons/m^3)/ live tree carbon (tons/ha)
= 800 × 0.2032/258
= 63 percent

Carbon in standing dead trees, predicted from growing stock volume. Estimates of carbon in standing dead trees are based on equations similar to those for live tree biomass (Smith et al. 2003). These estimates, based on live tree biomass as well as the same plot-level data used for live tree estimates, are as follows:

Table 5. Coefficients for estimating stand-level mass density in standing dead trees based on live tree biomass density and growing stock volume, from Smith et al. (2003, table 4).

Forest type[1]	Scale correction	Coefficients[2] A	B	C
		Entire tree		
Pacific Northwest, west side, hemlock–Sitka spruce[3]	0.89	0.2840	848.7	0.3790
Northern Lake States, aspen-birch	0.90	0.4176	127.0	0.4260
Southeast, oak-pine[4]	0.85	0.0510	826.8	1.3530
		Aboveground only		
Pacific Northwest, west side, hemlock–Sitka spruce[3]	0.89	0.2794	448.3	0.3440
Northern Lake States, aspen-birch	0.90	0.4211	124.4	0.4240
Southeast, oak-pine[4]	0.85	0.0512	868.3	1.2650

[1] *For additional forest types, see www.forestcarbon.net.*
[2] *Standing dead tree mass predictions are based on the following equation:*
Standing dead tree biomass density (metric tons per hectare) = (predicted live tree biomass density) × A × exp(–((volume/B)^C)).
[3] *Prediction based on general Pacific Northwest softwood relationship.*
[4] *Prediction based on general southern oak-pine relationship.*

Table 6. Coefficients for estimating carbon mass density of forest floor based on stand age, from Smith and Heath (2002, table 4).

Forest type[1]	Coefficients[2]			
	A	B	C	D
Pacific Northwest, west side, hemlock–Sitka spruce	87.5	116.7	27.5	16.0
Northern Lake States, aspen-birch	18.4	53.7	10.2	9.2
Southeast, oak-pine	15.4	20.1	10.3	3.8

[1] *For additional forest types, see www.forestcarbon.net.*
[2] *Forest floor carbon mass density (metric tons of carbon per hectare): Net accumulation with growth = (A × age)/(B + age) and decomposition following harvest = C × exp(–age/D).*

Standing dead tree mass density
= (Predicted live biomass density) × A × exp(–((volume/B)^C))

where the units for mass density are metric tons per hectare (dry weight); the units for volume are m^3 per hectare; and A, B, and C are coefficients, as shown in *table 5*. Carbon mass is 50 percent of standing dead tree mass.

▶ Example calculation for a northern Lake States aspen-birch forest with a growing stock volume of 120 m^3 per hectare, for above- and belowground stand-level mass density:
Standing dead tree mass density (entire tree)
= 148.9 × 0.4176 × exp(–(120/127.0)$^{0.4260}$)
= 23.4 tons per hectare dry weight
Standing dead tree carbon mass density
= 11.7 tons carbon per hectare

If this equation is applied to an average volume over a large area, the corrections for the effect of scale would be applied in the same manner as for live trees.

Carbon in the forest floor, predicted from stand age. The estimates presented here are based on region, forest type, and estimated stand age and history (Smith and Heath 2002). It is important to remember that the 50 percent ratio of carbon to biomass does not apply to the forest floor. Our estimates are in units of tons of carbon per hectare, based on the assumption that forest floor carbon mass at any given time is the result of simultaneous accumulation and decomposition processes. These processes can be represented by two relationships: (1) net accumulation with stand development and (2) estimated decay of mostly small woody residue after harvest. With reforestation (continuous cycles of harvest and replanting), forest floor carbon at any time is simply the sum of these two processes. With afforestation (conversion from nonforest to forest), only the net accumulation equation applies. The equations are as follows:

Net accumulation with growth, carbon density
= (A × age)/(B + age)
Decomposition following harvest, carbon density
= C × exp(–age/D)

where the units for forest floor carbon density are metric tons carbon per hectare, and age is in years; coefficients A, B, C, and D are provided in *table 6*. Note that coefficient C is the average forest floor carbon mass in metric tons per hectare for mature forests. This value can be used when age or history is unavailable.

▶ Example calculations for a southeastern oak-pine forest:
Oak-pine 50 years after harvest and regeneration
= (15.4 × 50)/(20.1 + 50) + 10.3 × exp(–50/3.8)
= 11.0 metric tons carbon per hectare
Oak-pine 20 years after converting pasture to forest
= (15.4 × 20)/(20.1 + 20)
= 7.7 metric tons carbon per hectare
Oak-pine forest of unknown or mixed age
= 10.3 metric tons carbon per hectare

Estimates Modified by Sampling Individual Pools

Sampling can provide locally specific information leading to greater resolution in one or more carbon pools. For example, local soil surveys may be preferable to regionwide averages, and down dead wood and understory vegetation may be strongly influenced by management practices specific to the site. Wherever such information is available for an individual carbon pool, one should simply substitute specific carbon data for the regional average.

Individual tree records, from mapped trees or cruise data, are another potential source to improve estimates for local conditions. Where individual tree measurements or known distributions of sizes are available, local tree biomass equations can be applied. The literature cited in Jenkins et al. (2003) and Jenkins et al. (in press) are useful for identifying candidate local equations to calculate tree carbon.

Discussion

The basic approach of the methods presented above involves assigning estimates of carbon stock based on FORCARB2 and FIA data. Extending the carbon stock values to form estimates of the potential for carbon accumulation in forest ecosystems is an essential part of a forest carbon budget. Net stock change, or carbon flux, is calculated as the difference in carbon stock over an interval divided by the time of the interval. This is a standard method for estimating net carbon flux in forests at large scales (IPCC et al. 1997; US EPA 2003), but it depends on changes in inventory variables over time. The first-pass method of assigning representative average carbon densities, as from *tables 1* and *2*, does not lend itself to estimating flux. However, additional information, such as projected volumes for a forest at two different times, is suited for determining stock change.

The examples of inventory-based estimates of forest carbon mass provided above are consistent with national estimates developed by the USDA Forest Service (US EPA 2003a, 2003b; USDA 2004a, 2004b). These same approaches can be applied to other forest types in the conterminous United States with the additional information from the forest carbon Internet site (www.forestcarbon.net) and the other sources cited above. More data for determining carbon stocks in forest ecosystems will become available in the near future. For example, data pertaining to carbon in down dead wood are being collected on a subset of FIA permanent inventory plots (Woodall 2003); we will use these data to help verify and update our current estimates. The forest carbon Internet site, which supplements this report, will include continual updates to reflect new data.

The estimators provided here were developed principally for large-scale assessments of forest carbon resources; that is, they were generally applied to areas extending from tens to hundreds of thousands of hectares. Overall precision of these forest carbon estimates varies depending on the application. For example, applying these methods to a specific woodlot would not provide a precise estimate of carbon mass for that site but rather an estimate of a regional average for similar sites. To improve precision of individual carbon sequestration projects, data should be collected from the project area. The more detailed inventory data collected for a site, the greater the precision of carbon estimates.

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