### Chapter 32.

# Carbon Sequestration
## in Loblolly Pine Plantations: Methods, Limitations, and Research Needs for Estimating Storage Pools

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**Abstract—***Globally, the species most widely used for plantation forestry is loblolly pine (*Pinus taeda *L.). Because loblolly pine plantations are so extensive and grow so rapidly, they provide a great potential for sequestering atmospheric carbon (C). Because loblolly pine plantations are relatively simple ecosystems and because such a great volume of knowledge has been gained about the species, the quantification of C dynamics of loblolly pine stands will be relatively easy. Here, we evaluate the state of science that relates to quantifying standing C pools in managed loblolly pine stands. We consider the accuracy and precision with which aboveground and belowground pools can be estimated, the portability of these tools across different stand types, and the intensity and efficacy of the measurement techniques. We emphasize the need to develop standard and relatively inexpensive measurement protocols.*

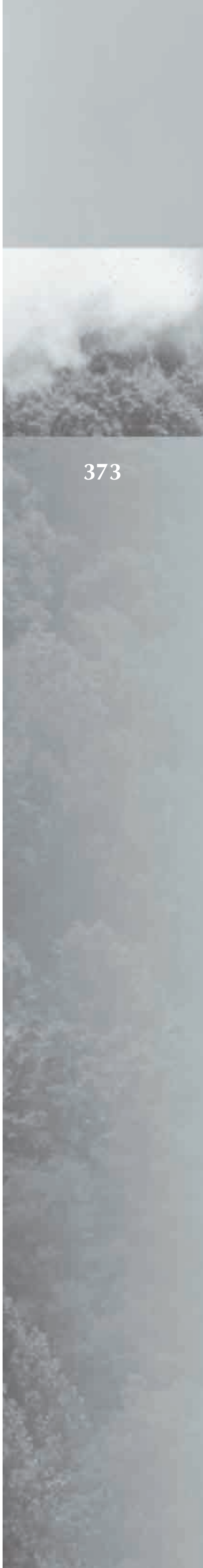
## INTRODUCTION

The Southern United States is now the most intensive and extensively managed forested area in the World. The tree species most widely employed in plantation forestry is loblolly pine (*Pinus taeda* L.). Because loblolly pine has great commercial and economic importance, its culture and management has been studied in great detail (Schultz 1997).

Although much practical knowledge has been gained about loblolly pine, the research has typically been aimed at providing information needed for commercial wood and fiber production. Such research has produced growth-and-yield models, artificial regeneration methodology, stand amelioration methodology (and especially that relating to fertilizer use), and information about forest genetics and tree improvement.

There is growing interest in quantifying the ability of forest trees to sequester atmospheric carbon (C). This interest stems from observed rapid increases in atmospheric carbon dioxide, an important greenhouse gas, and their potential for changing the Earth's climate. Because loblolly pine plantations are so extensive and grow so rapidly, they have great potential for sequestering atmospheric C (Johnsen and others 2001c). And because loblolly pine plantations are relatively simple ecosystems and because such a great volume of knowledge has been gained about the species, the quantification of C dynamics of loblolly pine stands will be relatively easy.

The quantification of C pools in loblolly pine stands is necessary for two main reasons. One benefit will be in developing and validating process models (Johnsen and others 2001a, 2001b). Conventional growth-and-yield models have been practical tools for managing loblolly pine stands, both naturally regenerated and plantation, over the past century. These models are based on empirical data about past performance and utilize site index to characterize stand quality



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and productive potential. Growth-and-yield models have been effective because the growth of the stands they are used for has typically been similar to the stands growth-and-yield tables were based on. However, with intensive forest management increasing, this assumption is no longer valid. Loblolly pine is being grown at unprecedented rates (Albaugh and others 1998, Samuelson and others 2001). Process models, which incorporate mechanistic information of tree and stand function, will hopefully provide tools for predicting stand performance under novel conditions. C, as a basic and major constituent of cellulose, lignin, starch, and sugars provides a valuable "currency" for models to be based on.

Process models are needed for more than managing stands of pine. Policy and planning with respect to the uncertainty of future climate and large-scale land management issues requires modeling tools that can provide useful forecasts. These efforts form the basis of the U.S. Department of Agriculture Forest Service, Southern Global Change Program. Clearly, information and tools developed to inventory stand C and model C dynamics at the managed pine stand level should be utilized to improve the performance of larger scale regional, national, and international modeling efforts.

Quantifying pine stand C pools will also provide a basis for "carbon credits." Although no system of C credits exists yet in the Southern United States, they are in serious consideration in Europe. It is clear that if C credits are to become a practical reality, standardized, dependable, but relatively simple protocols for quantifying C pools will be needed to accurately evaluate C sequestration over time.

In what follows, we evaluate the state of science that relates to quantifying standing C pools in managed loblolly pine stands. We consider the accuracy and precision with which aboveground and belowground C pools can be estimated, the degree to which estimation tools are applicable across different stand types, and the intensity of the measurement technique. We emphasize the need to develop standard and relatively inexpensive measurement protocols.

## PARTITIONING CARBON AMONG TREE ORGANS

A tree's total biomass resides within its stem, branches, leaves, reproductive organs, and root system. Biomass is allocated differentially among the aboveground and belowground components, and the proportions of biomass in different tissue components change during the course of stand development. For example, foliage can constitute up to 50 percent of a seedling's dry mass, but this proportion decreases greatly in older trees (fig. 32.1A). Figure 32.1A shows standing biomass components of fertilized trees at the Southeast Tree Research and Education Site (SETRES) (Albaugh and others 1998). Schultz (1997) stated that approximately 20 to 25 percent of standing biomass is present in root systems of mature trees, consistent with results from SETRES. In 1995, these stands had been fertilized for 3 years, and differential allocation among organs in terms of standing biomass was not strongly evident. However, figure 32.1B shows yearly production that indicates a much greater proportion of new growth allocated to both foliage and roots; fertilization reduced allocation to fine roots (data not shown). Both foliage and fine roots represent ephemeral organs. Thus, the proportions of standing biomass cannot be simply considered analogous to partitioning of total C gain.

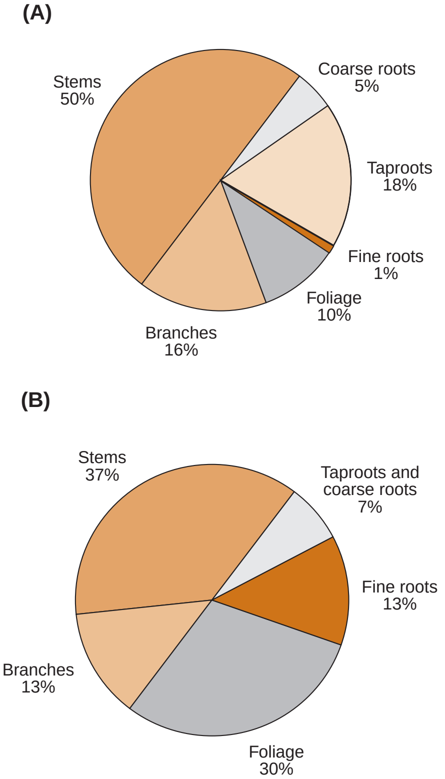

Figure 32.1—(A) standing biomass and (B) annual biomass production for fertilized trees from the Southeast Tree Research and Education Site located in North Carolina. The stand was established in 1985 and data are from 1995, 3 years after fertilization commenced.

## BIOMASS ESTIMATION

In several investigations, aboveground and belowground organs of trees have been harvested and the biomass of loblolly pine stands has been estimated, typically in a plantation setting. Often, relationships have been developed between simple metrics [diameter at breast height (d.b.h.) and height] and biomass components, and these relationships can be used to estimate site C. Although these studies can provide simple tools for estimating C pools, they are largely site, age, and/or tree size specific. In the following sections, we discuss the estimation of C for aboveground and belowground components using formulas available in the literature and other methods.

### *Aboveground Standing Carbon*

**Stems—**Figure 32.2 compares stem biomass estimates from six independently derived biomass equations at two tree size/age classes [only Baldwin (1987) uses age as a predictor]. Note that except for Van Lear and others (1984) and Naidu and others (1998), the larger size class examined in figure 32.2 represents a tree size larger than the sample trees examined in the studies. The larger size class was examined, though, because it represents a tree size frequently occurring during a full rotation. Except for Baldwin (1987), there is reasonable congruency among the estimates. However, confidence intervals are still large, and selecting the right equation to use for any particular site remains problematic. More such investigations are needed across a wider range of sites and tree sizes so that a stronger rationale can be developed for model selection. On a positive note, two sites that received extremely intensive management treatments (Albaugh and others 1998; Samuelson and others, in press) do not appear as outliers relative to the other sites that had less intensive management.

As boards and fiber are mostly contained in the boles of trees, many growth-and-yield tables for bole volume are available. For any given site, there are multiple growth-and-yield models to choose from. Again, we use SETRES as an example. Figure 32.3 shows the volume estimates provided by two growth-and-yield models: one from Goebel and Warner (1969) and one from Shelton and others (1984). Under all treatments, the Shelton and others model predicts approximately 50 percent higher volume than Goebel and Warner. The Goebel and Warner equation gives wood volume not total volume, i.e., no bark. The Shelton and others equation estimates volume outside bark. These are not trivial differences, especially for young trees, and probably account for a large part of the differences in volume estimates.

As with biomass equations, a systematic and nonsubjective method is needed for choosing the right growth-and-yield model for application to a particular stand. This will require a detailed evaluation and integration of the many models in the literature, as well as further research, particularly on intensive forestry systems. Landowners will need to provide nonsubjective simple biometrics such as height, d.b.h., and

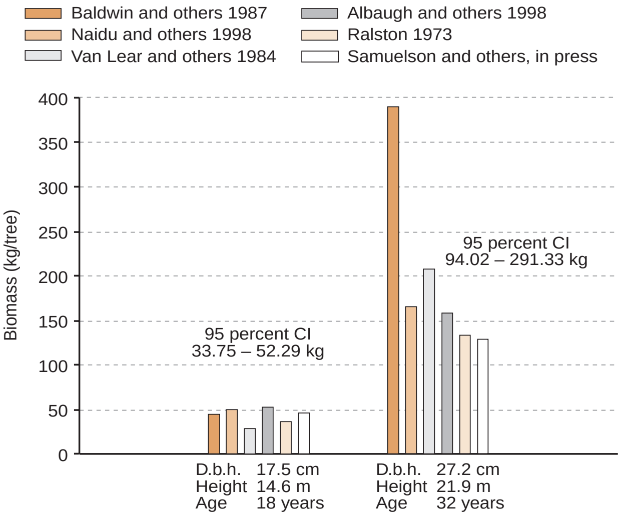

Figure 32.2—Stem biomass estimates obtained by applying six independently derived biomass equations for two tree size or tree age classes. Confidence intervals (CI) of 95 percent are shown for each size class.

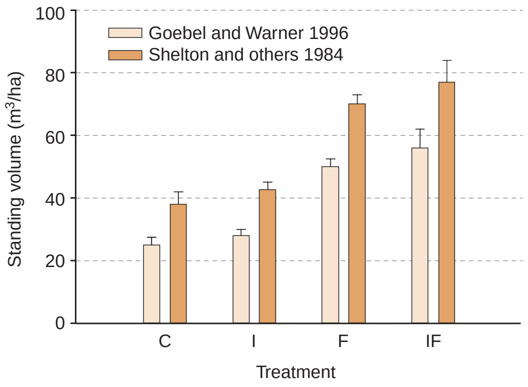

Figure 32.3—Standing volume estimates, using two growth-and-yield equations, for 10-year-old loblolly pine stand trees grown for the last 5 years under four treatments: control (C), irrigation (I), fertilization (F), and irrigation plus fertilization (IF). Treatments are described in Albaugh and others (1988).

stocking to a decision-support system that will use the appropriate growth-and-yield table (or biomass equation) and produce volume estimates.

Volume of stemwood, expressed as $m^3$/ha, is converted to Mg C/ha in the following way. First, multiply volume in $m^3$/ha by a value for the specific gravity of pinewood. Schultz (1997) suggests 0.5 is a good average to use. Then, because pine biomass is approximately one-half C, multiply the result by 0.5 to obtain an estimate of stemwood in Mg C/ha.

Zobel and others (1972) and Tauer and Loo-Dinkins (1990) demonstrated increasing specific gravity with tree age, and decreasing specific gravity with tree height, respectively, for loblolly pine. Concentrations of C vary among tree organs, ranging from 50 percent for branches to 42 percent for fine roots (Sampson and others 2001). In reality, specific gravity of wood as well as C concentrations of tree organs may vary with tree growth rate as influenced by management, and so both areas require further research and/or literature review to provide good estimates for application to a particular stand.

**Branches**—Branch biomass typically accounts for 10 to 20 percent of biomass (Shultz 1997). However, relatively little effort has gone into predicting stand branch biomass (Baldwin and others 1997). Branch biomass is strongly influenced by stand age and site quality (Hepp and Brister 1982). Again, the equations used to produce figure 32.2 also provide estimates for branch biomass, but stocking and productivity influences limit the portability of these relationships across sites.

**Foliage**—After planting, the quantity of foliage accretes over time until it reaches a semiplateau. Both the initial growth rate and the plateau reached are functions of site limitations. Therefore, in early stages of stand development, strong relationships are exhibited between metrics such as d.b.h. and height on the one hand, and leaf area or mass on the other hand. Once tree canopies close and a plateau in leaf mass is reached, such simple relationships may no longer exist. For larger trees, relationships between sapwood area and leaf area or mass will probably be more useful (Mencuccini and Grace 1995).

For midrotation stands like those at SETRES, the standing biomass of foliage of trees past the sapling phase is approximately 10 percent of total stand biomass. However, production of foliage biomass is much greater and at SETRES is approximately 30 percent of yearly biomass production. However, leaves represent the photosynthetic capital of a tree, and leaf biomass, or leaf area, is a major determinant of stand productivity. Leaf area dynamics are critically important in loblolly pine because the species maintains each cohort of leaves for two growing seasons so peak leaf area in late summer is approximately twice that in midwinter leaf area. Thus leaves are an important component of stand biomass, and yearly leaf area dynamics must be understood and modeled properly if stand productivity is to be modeled satisfactorily.

Leaf biomass can be determined from estimates of leaf area index (LAI), and vice versa, if estimates for specific leaf area ($g/m^2$) are also available. There are three common approaches to estimating leaf biomass and LAI. These include destructive biomass harvesting, litterfall techniques, and "instantaneous" techniques that employ measures of relative light flux density. Destructive harvesting is expensive and time consuming, and produces results that may be site-specific. Estimating LAI from littertrap data requires a waiting period, the length of which depends on both the number and longevity of individual annual foliage cohorts.

Instantaneous methods, such as using the LI-COR LAI-2000 Plant Canopy Analyzer (PCA), are rapid and much less expensive, and permit estimation of seasonal patterns in LAI when LAI varies monthly. However, the PCA underestimates LAI by 10 to 30 percent in pine stands (Sampson and Allen 1994), and corrections as shown in figure 32.4 are required. Estimation of

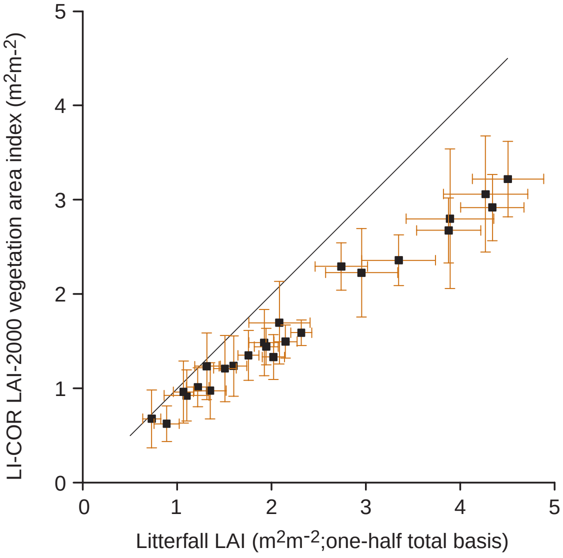

Figure 32.4—Relationship between litterfall, estimated leaf area index (LAI), and nondestructive measures using a LI-COR LAI-2000 from the Southeast Tree Research and Education Site.

seasonal foliage biomass or LAI using PCA will still require sequential measurements over time. In an attempt to minimize the sampling frequency, Sampson and others (in press) developed equations for estimating seasonal LAI from a single measurement. While this work utilized plots that varied greatly in productivity and stand structure, the general applicability of such an approach still needs to be tested.

### *Belowground Standing Carbon*

**Roots—**Taproots represent an important sink of C; intensive destructive sampling at SETRES showed that they constituted 15 to 18 percent of total tree biomass. Taproot excavation is extremely labor intensive. Heavy machinery can be utilized, but losses due to ripping and imprecision in the volume of soil sampled increase sampling error considerably. In the future, it will be necessary to develop inventories of stand taproot C on the basis of relationships between taproot C and simple measures such as d.b.h. and height, which will also be used to estimate aboveground biomass. Taproot morphology can vary tremendously within a stand. The four taproots shown in figure 32.5 came from trees on the same site in South Carolina and range from a single carrot-shaped root to a complex series of large sink roots stemming from a buttressed stem. Thus estimating total coarse root biomass removes the subjectivity involved in deciding exactly what constitutes the taproot.

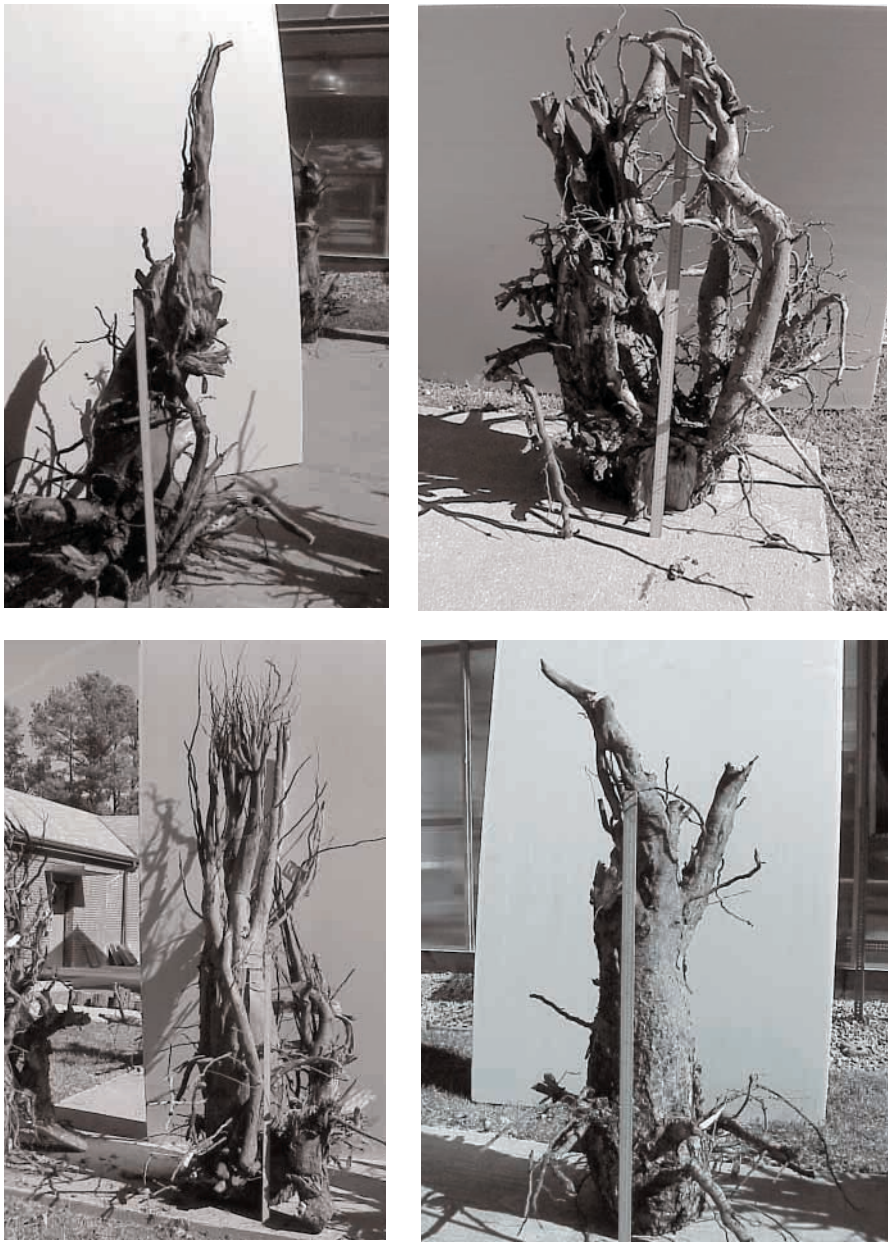

Figure 32.5—Taproots excavated from a 20-year-old plantation in South Carolina, showing the variation in root morphology. Photos by Lance Kress.

Figure 32.6 illustrates the relationship between coarse root biomass and total aboveground biomass for combinations of site and stand age. The figure shows total coarse root biomass because of the morphological differences discussed above. Log-log regression analyses of the data in figure 32.6 indicate that the allometric constant is approximately 0.20, which means that the ratio of coarse root biomass to aboveground biomass declines with stand development. Therefore, simple coarse root biomass:aboveground biomass ratios will not suffice. Note that these sites represent a large range in soil permeability (deep sand, clay, and loam), and so the fact that one relationship holds between coarse root biomass and aboveground biomass for all these sites is surprising. Relationships will likely have to be constructed for different site types. For example, a water table that is high or fluctuating or both may well reduce vertical taproot development.

Depending on soil and moisture conditions, taproots can penetrate below 3 m. Thus taproots reside in an environment that is not as conducive to rapid decomposition as finer root components and may be important in sequestering C belowground. Ludovici and others (2002) examined *in situ* decomposition of loblolly pine taproots grown on a Piedmont site across a 60-year chronosequence. Ten years following cutting, approximately 45 percent of taproot biomass persisted, and a small fraction was still recoverable after 60 years. These trees were of a size and age well beyond typical loblolly management standards for many areas of the South, and so taproot decomposition of more typical stands still needs to be assessed.

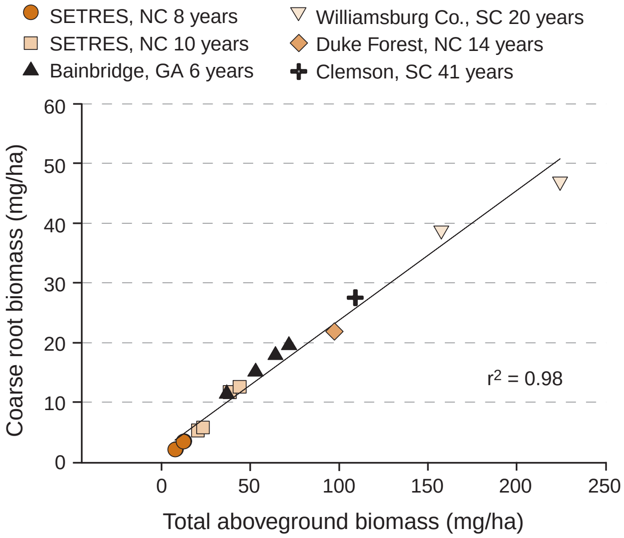

Figure 32.6—Relationship between aboveground biomass and coarse root biomass across sites. Note: All estimates are via biomass sampling except those for the Williamsburg site, where stem volumes were estimated using a volume equation and converted to carbon values as described in text and value was adjusted to add branch and leaf carbon using Baldwin and others (1997). Southeast Tree Research and Education Site (SETRES) estimates are via Albaugh and others (1998); Bainbridge, GA, from Samuelson and others (in press); Williamsburg, Co., SC; Duke Forest, NC, from Ralston (1973); and Clemson, SC, from Van Lear and others (1984, 1995).

The characterization of nontaproots into size classes is subjective. Often, fine roots are defined as being < 2 mm in diameter. As with leaves, fine roots represent an ephemeral tissue type. Thus the contribution of fine roots to total standing biomass can be low (fig. 32.1A). However, the contribution of fine roots to yearly production can be high (fig. 32.1B). Fine root production and biomass are affected by environmental conditions. For example, fertilization can greatly reduce fine root biomass production. Fine root biomass is often estimated by means of soil coring, which often requires high sample sizes as within-plot special variation can be extremely high. High-intensity root core sampling at a 20-year-old loblolly pine experiment in South Carolina demonstrated the great variation in root biomass and showed that the variation increases with profile depth as fine roots become scarcer (table 32.1A).

However, fine roots are much more homogeneously distributed than are coarser roots. Coarse root estimates derived via soil coring may in fact have little value in themselves. We have recently begun using an “air knife” that displaces soil by means of compressed air. Root systems can be excavated in a chosen area to a chosen depth around a sample tree; roots over 2 mm in diameter are left intact. This method appears to be superior to coring for estimating coarse root biomass.

As the sample size requirements in table 32.1A indicate, making precise estimates of root biomass is extremely difficult. Alternative methodologies need to be devised. Recently Butnor and others (2001, 2003) have explored the use of ground penetrating radar (GPR) to estimate root biomass. Because it provides an integrated measure, variability is actually lower in GPR estimates than in estimates obtained by coring. The use of GPR still requires that some coring be done so that GPR images can be calibrated. However, in 4 hours, the equivalent of over 2,000 cores’ worth of data can be collected using GPR, so sampling intensity can be increased greatly. Although GPR has shown promise on coarse-textured soils, much more work needs to be done so that it can

**Table 32.1—Site mean, mean square error, and estimated sample size needed, by soil profile depth, to detect 10-percent differences between treatment means for root biomass (A) and percent soil carbon (B)[a]**

| Depth | Mean root mass | MSE | Sample size |
|---|---|---|---|
| *cm* | *g/core* | | *10% difference* |
| A | | | |
| 0–20 | 16.88 | 15.91 | 679 |
| 20–40 | 0.62 | 1.85 | 7,296 |
| 40–60 | 0.57 | 1.18 | 3,336 |
| | Mean % carbon | | |
| B | | | |
| 0–20 | 2.09 | 0.96 | 176 |
| 20–40 | 0.28 | 0.28 | 167 |
| 40–60 | 0.24 | 0.24 | 276 |

MSE = mean square error.

[a] Data is from a sample of 240 10-cm diameter soil cores collected from a 20-year-old North Carolina State Forest Nutrition Cooperative Regionwide 7 trial in Williamsburg Co., SC.

be applied across more soil types. However, both antennae optimization and rapid improvements in data processing make it likely that GPR will provide a very powerful and useful tool for estimating root biomass.

**Soil Carbon—**Soil C often is the largest component of a stand's total C stock. Soil C is typically sampled by coring, often in combination with root sampling. As with roots, soil C decreases with depth (table 32.1). Soil C is more homogeneous than root biomass, however, and this is reflected in the lower coefficients of variation and sample size requirements for soil C (table 32.1). However, sampling intensity needs to be high, and sampling therefore can be very costly.

If one is to take cores for soil C analyses, one must decide whether to core by horizon or by standard depths. Coring by horizon is more difficult as it requires locating the horizon depths for each sample, but it can reduce variation among samples and thus decrease sample sizes. Coring by depth is more rapid, but as soil profiles will often change within a depth increment, variation among samples will be higher. The tradeoffs between the two protocols need to be established before one chooses a sampling scheme.

If large cores with a known soil volume are used, then data can simply be scaled to the stand level volumetrically. Where small soil augers are used, soil bulk density must be assessed so that soil C data can be scaled up. Although soil C concentrations typically decrease with depth, soil bulk density increases also, and so values of both characteristics must be determined to properly scale the data to the stand level.

In managed stands, soil C can display large temporal variation. After clearcutting, root biomass soon becomes necromass and decomposes over time, resulting in a large temporary increase in soil C. This phenomenon is clearly shown in figure 32.7, which displays soil C results of a long-term site productivity study in the Croatan National Forest in North Carolina. During year zero, the old stand was cut and replanted. After only 1 year, soil C increased, probably as a result of the decomposition of the least recalcitrant fine roots from the harvested stand. By year five, soil C peaked as larger root classes decomposed. By year ten, the strong pulse of organic matter was largely lost due to soil respiration. However, soil C concentrations were still higher than at year zero. If C sequestered in the soil is to be quantified properly, these fluctuations over time must be taken into account. Although the soil C pulse is ephemeral, it still results in a net exclusion of C from the atmosphere.

Again, the variability among soil C measurements is large and indicates that new methodologies must be devised. Currently workers are exploring the possibility of using advanced Raman/SERS fiberoptic-based devices (Wullschleger and others 2001), Laser-Induced Breakdown Spectroscopy (Ebinger and

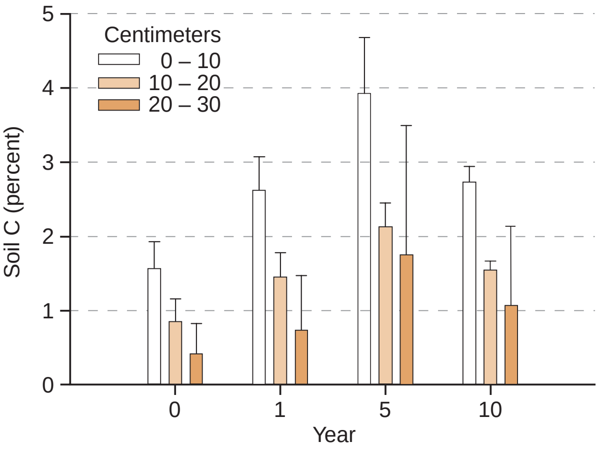

Figure 32.7—Percent soil carbon (C), by soil profile depth, over time, for stands from the long-term site productivity experiment located in the Croatan National Forest in coastal North Carolina. The previous stand was harvested and the new stand planted in year zero.

others 2001), and inelastic neutron scattering (Wielopolski and others 2000) to analyze and characterize C concentration in soil.

## CONCLUSIONS

Clearly land will rarely if ever be managed solely for sequestering atmospheric C. However, C sequestration can provide a cobenefit, and the possibility of receiving income provided for C credits would often affect land management decisions about management intensity and rotation length.

Obviously sampling, site, and temporal variation is associated with measuring each of the stand components discussed above. We have indicated where we think further research is needed both to improve the precision of estimates and to make estimation easier. Increased collaboration among researchers in the Southern United States will produce great gains.

True quantification of C sequestered by managed forests will require assessing the temporal variation of the various C pools, integrating each curve, summing the integrated values, and then dividing the sum by rotation length. Models can be developed so that integrated values can be estimated from measurements made at critical times in a plantation's development. Alternatively, landowners could be credited for C on a site each year, relative to some standard base level. However, in the latter method, C deficits following stand harvesting and planting would require that a landowner actually pay for negative C credits until accreted C again reaches the baseline C level. This manner of executing C credits would obviously be extremely difficult and expensive.

We envision at least two tiers of precision in estimates of standing C for the purposes of documentation for C credits. At the coarser level, the landowner might provide only basic stand information such as d.b.h., height, and stocking. All conversion factors, as well as soil C values, would then be obtained from the literature and might be stratified to provide different estimates for different regions, soil types, and management intensity. This level of precision would likely be suitable for most small private landowners.

At finer and more precise levels, the landowner would provide more specific stand data. These could include direct estimates of soil C, root biomass, specific gravity, C concentration of tree tissue, and leaf area. These levels of precision would more likely be used by forest industries, and especially those with strong internal research programs or cooperative research programs with agencies and universities.

The value of C credits would then likely increase as the direct inputs into estimates increase. The financial gain made by providing more direct information for stands will determine the willingness of landowners to collect and provide more data. It is possible that consulting companies will proliferate. These consultants would be geared up to use state-of-the-art tools, and would incorporate field data into state-of-the-art models to provide C sequestration estimates. In any case, all estimates provided for C credit documentation will need to be certified for authenticity.

## ACKNOWLEDGMENTS

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