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Measuring carbon in forests: current status and future challenges

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"Capsule": *Carbon in forests can be measured accurately now, with future measurements relying more on remote sensing and other remote data collecting techniques.*

Abstract

To accurately and precisely measure the carbon in forests is gaining global attention as countries seek to comply with agreements under the UN Framework Convention on Climate Change. Established methods for measuring carbon in forests exist, and are best based on permanent sample plots laid out in a statistically sound design. Measurements on trees in these plots can be readily converted to aboveground biomass using either biomass expansion factors or allometric regression equations. A compilation of existing root biomass data for upland forests of the world generated a significant regression equation that can be used to predict root biomass based on aboveground biomass only. Methods for measuring coarse dead wood have been tested in many forest types, but the methods could be improved if a non-destructive tool for measuring the density of dead wood was developed. Future measurements of carbon storage in forests may rely more on remote sensing data, and new remote data collection technologies are in development.

Keywords: Aboveground biomass; Root biomass; Carbon budgets; Coarse woody debris; Remote sensing; Videography

1. Introduction

The ability to accurately and precisely measure the carbon stored and sequestered in forests is increasingly gaining global attention in recognition of the role forests have in the global carbon cycle, particularly with respect to mitigating carbon dioxide emissions (Brown et al., 1996; Kauppi and Sedjo, 2001). On a global scale, changes in forest cover have historically been, and are currently, net sources of carbon dioxide, the main greenhouse gas (GHG), to the atmosphere (Houghton, 1999; Houghton and Hackler, 2001). Forests are influenced by natural and human causes, including harvesting, over-harvesting and degradation, large-scale occurrence of wildfire, fire control, pest and disease outbreaks, and conversion to non-forest use, particularly agriculture and pastures. These disturbances generally cause forests to become sources of CO_2 because net primary productivity is exceeded by total respiration or oxidation of plants, soil, and dead organic matter. At the same time, however, some areas of harvested and degraded forests or agricultural and pasture lands are abandoned and revert naturally to forests or are converted to plantations, thus becoming carbon sinks, i.e. the rate of respiration from plants, soil and dead organic matter is exceeded by net primary productivity.

There are two key policy-related reasons for measuring carbon in forests: (1) commitments under The United Nations Framework Convention on Climate Change (UNFCCC), and (2) for potential implementation of the Kyoto Protocol. The UNFCCC, signed by more than 150 countries, requires that all Parties to the Convention commit themselves to develop, periodically update, publish, and make available to the Conference of Parties (COP) their national inventories of emissions by sources and removals by sinks of all GHGs using comparable methods (Houghton et al., 1997). Land-use change and forestry is one sector for which a national inventory of sources and sinks of GHGs must be developed. With reference to forests, the inventory must include estimates of carbon emissions and removals caused by changes in forest biomass stocks due to forest management, harvesting, plantation establishment, abandonment of lands that regrow to forests, and forest conversion to non-forest use. All these changes imply

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that measurements of carbon in biomass stocks must be made.

The recognition that forestry activities could be both sources and sinks of carbon led to their inclusion in the Kyoto Protocol. There are several articles in the Protocol that refer to forests: Article 3.3 refers to emissions by sources and removals by sinks resulting from direct human-induced activities limited to afforestation, reforestation and deforestation; Article 3.4 refers to additional human-induced activities in forestry (among other changes in land use); Article 6 refers to the trading of emissions reduction units in any sector of the economy; and Article 12 refers to emission-offset trading between developed and developing countries; however, forestry projects are not explicitly mentioned in this article and whether they will is still being debated. All of these articles refer to the emissions and removals as being real, measurable, and verifiable changes in carbon stocks.

All of the aforementioned articles in the Kyoto Protocol concerning the role forests can play in the global carbon cycle emphasize that the activities must be human-induced. However, other factors besides direct human-induced, such as annual variation in climate and rising atmospheric CO_2 and nitrogen concentrations, can affect the carbon stocks of forests. Attributing the change in carbon stocks of forests to a given cause can be challenging but needed if the carbon accounting is to be in accordance with the articles of the Kyoto Protocol. A recent re-assessment of the global carbon budget suggests that terrestrial ecosystems appear to be a net sink for atmospheric carbon, even when losses due to land-use change are taken into account, and that the magnitude of the sink increased between the 1980s to 1990s (Bolin and Sukumar, 2000). For the 1980s, the net sink was 0.2 ($\pm$1.0) Pg C/year, and for the 1990s this had increased to 0.7 ($\pm$1.0) Pg C/year (Bolin and Sukumar, 2000). The terrestrial net carbon sink is due to the net effect of land-use practices (e.g. agricultural abandonment and regrowth, deforestation, and degradation), the indirect effects of human activities (e.g. atmospheric CO_2 fertilization and nitrogen deposition), and the effects of changing climate, climatic variation, and disturbances. At a global level, therefore, significant changes in terrestrial carbon stocks occur that are unrelated to direct human interventions.

Regional source and sink relationships have been inferred by the techniques of inverse modelling of observed atmospheric CO_2 gradients and circulation patterns (Ciais et al., 1995; Fan et al., 1998). For example, the study by Fan et al. (1998) suggested that 1.4 Pg C/year were taken up by the terrestrial biota in North America in the 1980s. However, these estimates are relatively imprecise, and are difficult to relate to those based on forest inventory data. Mechanistic models and measurements based on forest inventories do not agree with either the magnitude or spatial distribution of the carbon sink proposed by Fan et al. (Holland and Brown, 1999; Potter and Klooster, 1999). Improved accuracy and precision of measurements of carbon in forests as well as the history of forest land use would help resolve the ongoing inconsistencies in the global terrestrial carbon cycle (Caspersen et al., 2000; Schimel et al., 2000).

The purpose of this paper is (1) to review the methods and procedures currently available and (2) to discuss needs for improving the existing methods for measuring carbon stocks in the main live and dead (excluding soil) components of forests to address the policy-related issues described above. If carbon stocks can be measured accurately and precisely, measurements over time, using the same approaches, would provide the necessary information to determine changes in carbon stocks as required by the UNFCCC and forestry projects for mitigating carbon emissions. The focus of the paper will be on practical measurements of carbon in aboveground live biomass, belowground biomass, and dead woody biomass. In general, the biomass of understory and fine litter are a small fraction of the total carbon in most forests (with the exception of open woodlands and young successional forests) and methods for measuring these components are well established and will not be discussed further here. Measurements of soil carbon will also not be addressed here. I will conclude the paper with a brief discussion on the precision of carbon measurements, and the future role of remote sensing in measuring carbon in forests.

2. Measurement of forest carbon pools

2.1. Aboveground biomass

For existing forests, inventory data are the most practical means for estimating aboveground biomass carbon as the data are generally collected at the required scales and from the population of interest in a statistically well-designed manner. Practically all developed countries conduct regular national inventories of their forests (UN ECE/FAO, 2000). Many tropical countries have at least one inventory of all or part of their forest area, although many of the inventories are more than 10 years old and very few have repeated inventories (UN FAO, 1993; Brown, 1997). Data from these inventories can be converted to biomass carbon in one of two ways depending upon the level of detail reported (Brown, 1997).

Failing the existence of inventory data for forests, as might be the case for many tropical forests or for project-scale activities such as included in Article 3.3 of the Kyoto Protocol, methods are well established and tested for designing a sampling scheme, including estimating the number, size, and distribution of permanent plots for a given level of desired precision (MacDicken, 1997a, b). Once plots are established, the biomass of trees and dead wood can be estimated from standard measurements as described below. For tracking changes in carbon stocks of forests, experience has shown that tagging trees with a unique number is the preferred approach—this way the fate of all trees can be tracked as they accumulate carbon, new ones enter the minimum diameter size (ingrowth) or trees die (Clark et al., 2001).

Two methods are generally used to convert field measurements of trees to aboveground biomass. If merchantable volume of all species to a known minimum diameter (often about 10 cm or so) is reported, simple models have been developed to convert this to biomass using biomass expansion factors (e.g. Brown et al., 1989; Birdsey, 1992; Brown and Lugo, 1992; Brown, 1997; Schroeder et al., 1997; Brown and Schroeder, 1999). For earlier work on carbon budgets in the USA, a constant biomass expansion factor (BEF = ratio of total aboveground biomass to merchantable volume) by forest type was used to convert volume to biomass (Birdsey, 1992). Other work in the tropics and later work on US forests showed that the magnitude of the BEF varies with the merchantable volume of the stand—high BEFs at low values of volume, and generally decreasing exponentially to a constant BEF at high volume (Fig. 1). Pines are the exception to this general rule, and instead the biomass expansion factors decrease sharply at low merchantable volume, and then remain relatively constant across all volumes. Tropical hardwoods tend to have higher biomass expansion factors for a given volume than do temperate hardwoods.

If the forest inventory data report individual tree diameters or stand tables (number of trees per unit area by diameter classes) then these data can be converted to biomass directly by using allometric biomass regression equations. Such equations exist for practically all forests of the world; some are species specific and others are more generic in nature. For example, Brown (1997), Schroeder et al. (1997), and Brown and Schroeder (1999) have found that pooling by general species groups such as tropical moist or wet hardwoods, temperate eastern US hardwoods, pines, and spruce species produce highly significant regressions equations

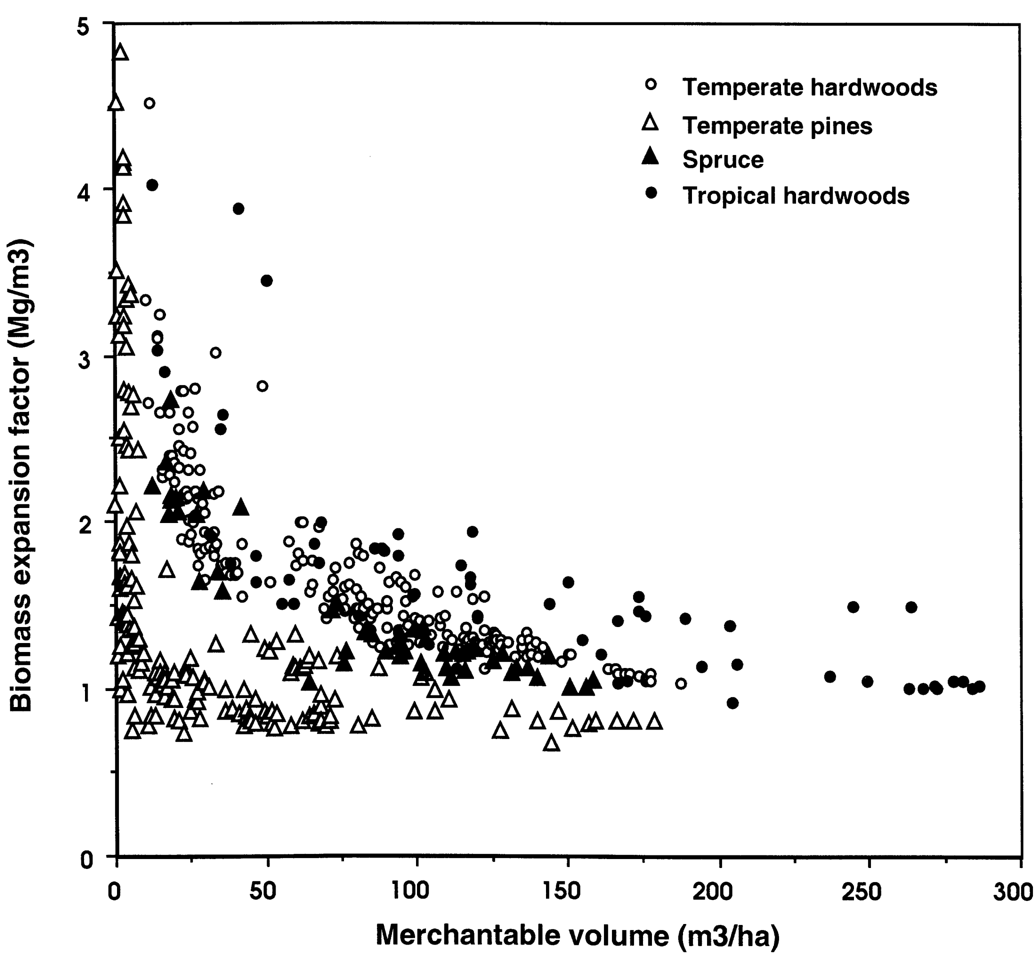

Fig. 1. Relationship between biomass expansion factors (ratio of total aboveground biomass to merchantable volume) for temperate hardwoods, pines and spruce, and tropical hardwoods (data from Brown et al., 1989; Brown and Lugo, 1992; Schroeder et al., 1997; Brown et al., 1999).

between diameter at breast height (dbh) only and biomass per tree, with r^2 of 0.98 or more. Inclusion of height in the regression equation can improve the r^2 and increase the precision, but measuring height of all trees across a large number of plots or an inventory can be very time consuming and often extremely difficult as the top of tall emergent trees can be almost impossible to see. Thus for practical purpose, regression equations based on diameter alone, and stratified by species groups or by climate type, are more useful.

Sampling a sufficient number of trees to represent the size and species distribution in a forest to generate local allometric regression equations with high precision, particularly in multi-species forests, is extremely time-consuming and costly. The advantage of using generic equations, stratified by, e.g. ecological zones or species group (broadleaf or conifer), is that they tend to be based on a large number of trees (e.g. Brown, 1997; Brown and Schroeder, 1999) and span a wider range of diameters; this increases the accuracy and precision of the equations. It is very important that the database for biomass regression equations contain large diameter trees as these tend to account for a large proportion of the aboveground biomass in mature forests; often between 30 and 40% of the aboveground biomass can be found in trees with diameters greater than 70 cm (Brown and Lugo, 1992; Brown et al., 1997). A disadvantage is that the generic equations may not accurately reflect the true biomass of the trees in the project. In most cases, several sample trees, in larger diameter classes, should be destructively harvested to test the validity of the selected generic equation.

In the USA, there is a vast network of permanent sample plots (about 1 plot per 2400 ha of forest land across the landscape) that make up the Forest Inventory and Analysis (FIA) and Forest Health Monitoring (FHM) programs (more information can be obtained from http://fia.fs.fed.us/about.htm). The FIA program has been in operation for about 70 years and covers forests on all private lands and most public lands. The programs report on, among other variables, the status and trends in forest area and location; individual tree measurements of diameter, species, and health; and growing stock volume, increment, mortality, and removals by harvest. Data for the eastwide plots (33 eastern states) can be readily downloaded in varying degrees of detail from the following website: http://www.srsfia.usfs.msstate.edu/scripts/ew.htm. Using the eastwide data base at the county scale, Brown et al. (1999) and Brown and Schroeder (1999) estimated aboveground biomass and aboveground production and mortality of biomass for softwood and hardwood forests of the eastern USA at the county scale of resolution (Fig. 2). Most softwood forests have aboveground biomass in the range of 50–150 Mg/ha (or 25–75 Mg C/ha) with production of biomass in the range of 2.5–10 Mg $ha^{-1}year^{-1}$ (or 1.3–5 Mg C $ha^{-1}year^{-1}$; Fig. 2a). Most of the hardwood forests have aboveground biomass in the range of 75–175 Mg/ha (or 38–90 Mg C/ha) and production rates of 3–7.5 Mg $ha^{-1}year^{-1}$ (or 1.5–3.8 Mg C $ha^{-1}year^{-1}$; Fig. 2b).

For newly reforested or afforested areas that might be established to meet the goals of Article 3.3 of the Kyoto Protocol, a system of permanent sample plots would need to be established using standard statistical sampling design procedures as described above. If these types of reforestation/afforestation activities were established across many private land owners, the sampling design would need to account for this. Depending on the planned activity and location, it is possible that the land owners could form a consortium of their combined lands to reduce the measurement costs. Furthermore, depending on the species to be planted, species-specific regression equations could be developed to more accurately estimate the biomass carbon.

It is often assumed in inventories that small trees (about 10 cm diameter or less) contribute little to the total biomass carbon of a forest and thus they often tend not to be measured. However, their contribution depends on the successional stage of the stand. For example, for young hardwood stands in the eastern USA with aboveground biomass of 50 Mg/ha or less, the biomass of the trees with dbh of 10 cm or less contained as much as 75% of the biomass in trees with dbh greater than 10 cm (Schroeder et al., 1997). The proportion dropped to 10% for stands with aboveground biomass of >175 Mg/ha. Thus for most temperate hardwood forests, ignoring the small diameter trees may significantly underestimate the total carbon storage in live biomass.

2.1.1. Data needs to improve aboveground biomass estimates

There are several areas that could be improved to more accurately and precisely estimate the carbon storage in aboveground live tree biomass, including:

1. More large diameter trees need to be destructively harvested and their biomass measured to add to the existing data sets for developing biomass regression. These additional harvested trees could be pooled by species groups for mixed forests. The existing equations are based on a data set that lacks an adequate number of large diameter trees—large diameter trees have a marked influence on the shape of the regression. For example, a data base of 454 trees of US eastern hardwood trees (Schroeder et al., 1997), contains only 16 trees with diameter >60 cm.
2. Wetland forests and plantations have fewer tree species, and species-specific biomass regression

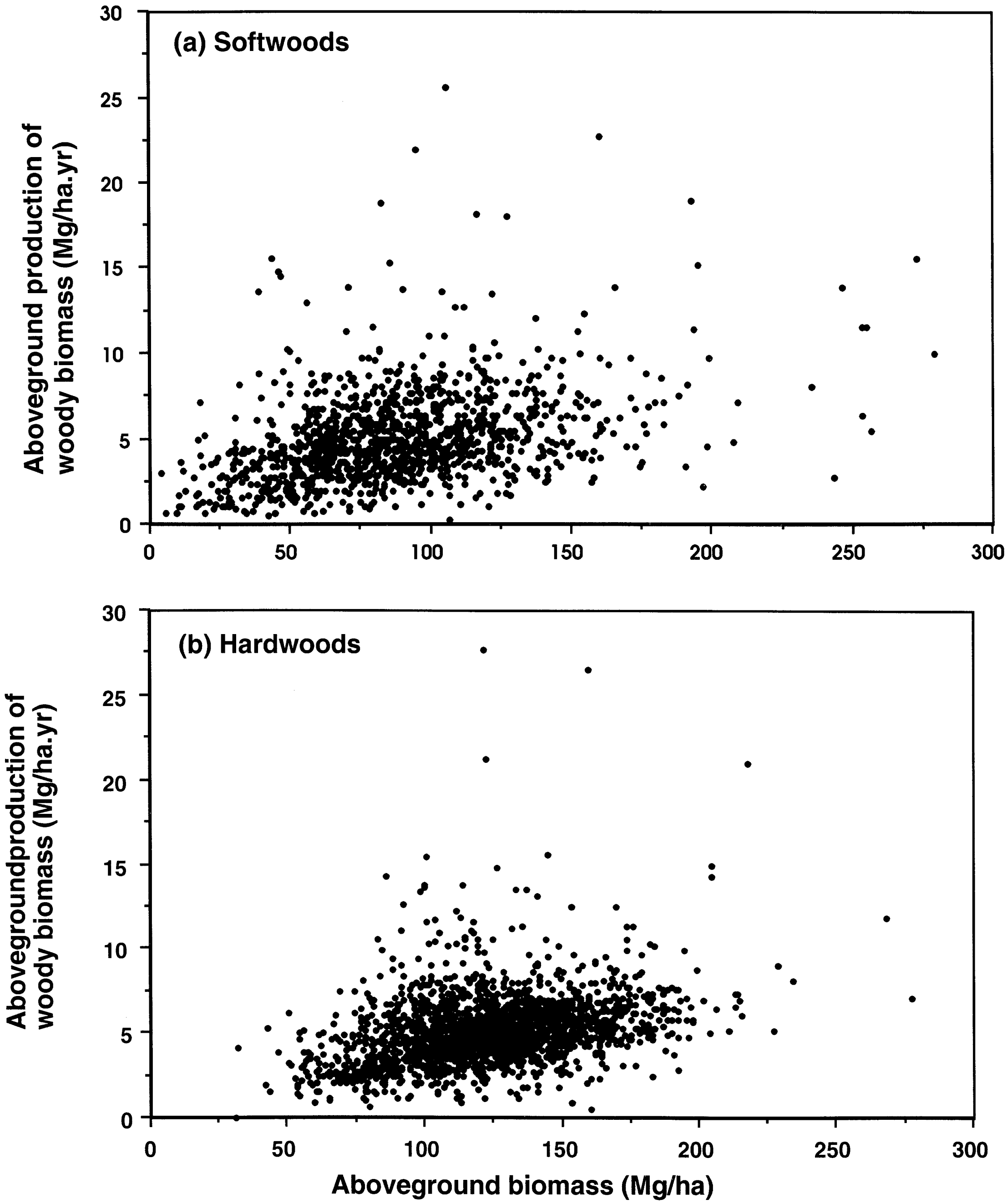

Fig. 2. Scattergraphs of aboveground production of woody biomass versus aboveground biomass for (a) softwoods and (b) hardwoods. The values are forest area-weighted averages at the county scale of resolution for about 1950 counties in 28 eastern US states (data are from Brown and Schroeder, 1999).

equations need to be developed for these forest types. The data base for these species needs to make sure that it contains trees that span the full range of diameters, especially the larger diameters.

3. Most of the existing biomass regression equations are based on trees that were harvested in the period late 1960s to early 1980s. A question is, have trees changed their allometries under the ongoing global change? This question needs to be addressed by comparing more recently collected data with earlier measurements.
4. Efforts need to be made to collate and archive all original allometric data on tree biomass and made freely available on the internet—this is a task the US Forest Service could organize as part of their inventory program and made available on their web site.

2.2. Belowground biomass

As described earlier, measuring aboveground biomass is relatively well established; however, the biomass of roots is difficult and time consuming to measure in any forest ecosystem and methods are generally not standardized (Körner, 1994; Kurz et al., 1996; Cairns et al., 1997). A review of the literature shows that typical methods include spatially distributed soil cores or pits for fine and medium roots and partial to complete excavation and/or allometry for coarse roots. The distinction between live and dead roots are generally not made and so root biomass is generally reported as total live and dead. Moreover, depths of sampling are not standardized, but the depth selected in a given study is assumed to capture practically all roots.

Root biomass is often estimated from root:shoot ratios (R/S). A recent literature review by Cairns et al. (1997) included more than 160 studies covering tropical, temperate, and boreal forests that reported both root biomass and aboveground biomass. The mean R/S based on these studies was 0.26, with a range of 0.18 (lower 25% quartile) to 0.30 (upper 75% quartile). The R/S did not vary significantly with latitudinal zone (tropical, temperate, and boreal), soil texture (fine, medium and coarse), or tree type (angiosperm and gymnosperm). Further analyses of the data produced a significant regression equation of root biomass density versus aboveground biomass density when all data were pooled (Fig. 3). Inclusion of age or latitudinal belt improved the adjusted r^2 to 0.84, which although small was significant (Cairns et al., 1997). However, variability was large around the root biomass estimates calculated from the regression (Fig. 3). The variability is likely due not only to the natural variability in forests and the use of different sampling methods, but also to the lack of a systematically, statistically rigorous experimental design executed with the same sampling methods. If the data point were proportionally derived from all conditions of latitude, soil texture, age, tree type, and aboveground biomass it is likely that the variability would be less.

The equation presented in Cairns et al. (1997) can be used to make estimates of root biomass in a standard manner for forests based on knowledge of the aboveground biomass. Use of these equations for estimating root biomass of unique forests such as wetlands may not be appropriate because of additional site or climatic characteristics.

2.2.1. Data needs to improve belowground biomass estimates

From the earlier discussion, I believe that the most practical and cost-effective approach for estimating belowground biomass is to improve the model of root biomass based on aboveground biomass. To improve the model, the following data are needed:

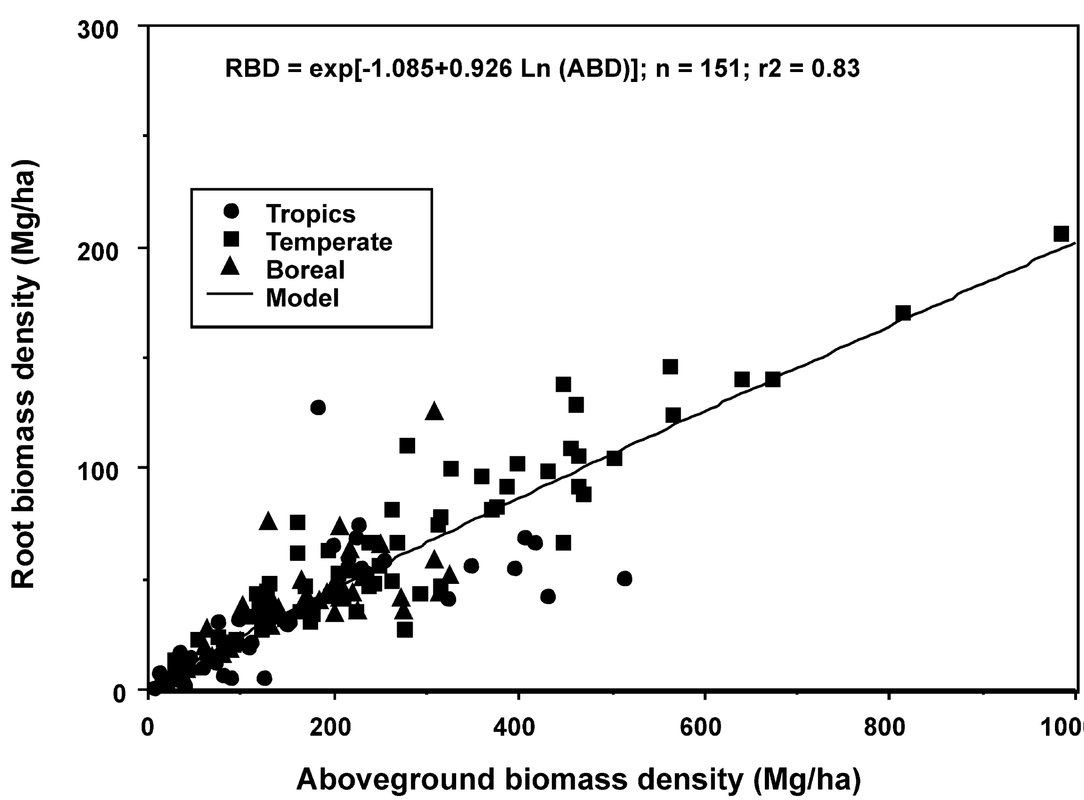

Fig. 3. Relationship between root biomass density (RBD) and aboveground biomass density (ABD; data are from Cairns et al., 1997).

1. The existing data base is limited and does not cover all conditions of latitude, soil texture, age, tree type, and aboveground biomass. For US forests, a rigorous experimental design using the same methods needs to be implemented to fill this need.
2. Greater attention needs to be given to measurements of coarse and butt roots, which account for the largest proportion of root biomass [on average about 70% or more of the total root biomass (Cairns et al., 1997)]. Development of further allometric regression equations of coarse and butt root biomass versus tree diameter, for the same conditions given in the previous paragraph would meet this need.

2.3. Dead wood biomass

Dead wood is generally divided into coarse and fine, with the breakpoint set at 10 cm diameter (Harmon and Sexton, 1996). Although coarse dead wood, including standing and lying, is often a significant component of forest ecosystems, often accounting for 10–20% of the aboveground biomass in mature forests (Muller and Liu, 1991; Harmon et al., 1993; Delaney et al., 1998), it tends to be ignored in many forest carbon budgets. The quantity of dead wood does not generally correlate with any index of stand structure (Harmon et al., 1993). The production of dead wood in US forests can be estimated from tree mortality, which is tracked as part of the repeated measurements of the FIA plots. Average rates of production of dead wood for hardwood and softwood forests in the eastern USA from natural mortality have been estimated at about 1 Mg $ha^{-1}year^{-1}$ (Brown and Schroeder, 1999). Substantial quantities of slash and large debris are often left in forests after harvesting operations; however, the usefulness of the reported data on harvest on the FIA website for estimating slash would need to be assessed. For eastern US forests, the amount of slash produced has been estimated to equal that produced by natural mortality (Brown and Schroeder, 1999).

Methods have been developed for measuring biomass carbon in dead wood and have been tested in many forest types and generally require no more effort than measuring live trees (Harmon and Sexton, 1996). The first step in measuring dead wood is to estimate the volume using one of several tested techniques. The dead wood is then classified into one of several decomposition classes. Samples of dead wood in each decomposition class are then collected to determine their wood density. Mass of dead wood is then the product of volume per decomposition class and density for that class. Thus, a key step in the present methods is classifying the dead wood into its correct decomposition class and then adequately sampling a sufficient number of logs in each class to represent the wood densities present.

The use of decomposition classes assumes that the state of decomposition is correlated to its density. However, this is not always the case, especially in those species that have very resistant heartwood—they can be in an advanced state of decomposition having lost all the bark and sapwood yet the heartwood can still be very sound and dense as is often the case in many tropical species (Harmon and Sexton, 1996; Delaney et al., 1998). Instead of decomposition class, it might be more useful if a tool to measure a density scale could be developed.

2.3.1. Data needs to improve dead wood biomass estimates

Improvements in estimating dead wood biomass could be achieved by the following:

1. Development of an objective, non-destructive portable tool for measuring the density of dead wood regardless of its decomposition class; this most likely requires the development and application of new technology.
2. Compile the existing data on dead wood densities by decomposition class and by forest type—there is a substantial quantity of data on dead wood densities scattered throughout the world and every effort needs to be made to collate this in one locale (maybe as part of the US Forest Service FIA program).
3. Assess the usefulness of the harvest data in the US Forest Service's FIA data base for estimating the amount of logging slash left behind.

3. Precision of carbon measurements

Although the above methods for measuring carbon in the main forest components are likely to be reasonably accurate, a key concern for implementing the articles of the Kyoto Protocol is how precise the measurements are. The total error in measuring a given carbon pool is based on sampling error (the variation among sampling units, e.g. the number of plots, within the population of interest) measurement error (error in measuring the parameter of interest, e.g. stem diameter and soil carbon) and regression error when appropriate (e.g. error resulting from conversion of tree diameter to biomass based on a regression equation). Efforts are being made to quantify all these sources of error and how they propagate to determine the overall error in carbon stocks and changes in carbon stocks (Heath and Smith, 2000; Phillips et al., 2000; Smith and Heath, 2001).

Phillips et al. (2000), using an analytical statistical approach, estimated the measurement error, sampling error, regression error, and total error for growing stock volume, and average annual net volume growth, removals, and change in growing stock volume for forests of the five states of the southeastern FIA unit of the United States for a 6–8 year inventory period. Their analysis indicated that for the region-wide quantities given above, the total error, expressed as the 95% confidence interval of the mean, was ±1% for growing stock volume, ±2 to ±3% for net volume growth and removal, and almost ±40% for change in growing stock volume. The sampling error was the largest component of the total error in these examples, accounting for 90–99%. Analysis of the data at smaller scales, such as the county level, would result in a larger confidence interval, mostly due to the increase in sampling error at this smaller scale.

The work by Heath and Smith (2000) and Smith and Heath (2001) used Monte Carlo analysis (a numerical approach to propagating model uncertainty) with a forest carbon budget simulation model. They used estimated ranges of uncertainty around the input parameters, and simulated the model several hundred times using a random selection of parameter values within the defined ranges. They found that the uncertainty range for the carbon inventory for all US forests was 9–11% of the median value for a range of years simulated, and that the uncertainty in the change in carbon stocks was considerably higher and more variable from year to year, as was found by Phillips et al. (2000). The value of the Monte Carlo analysis is that it helps identify which parameters are most influential on the uncertainty in the carbon budget, and thus helps focus where research efforts are needed (Heath and Smith, 2000). For the US forest carbon budget, they found that soil and tree carbon were most influential on the uncertainty for the carbon stock inventory and growth and removals were most influential on the uncertainty in the change in carbon stocks.

Currently, there are no policy guidelines for national inventories nor for activities that could be implemented under the Kyoto Protocol as to the level of precision to which carbon stocks and their change should be measured. Setting such a level would facilitate comparison of national inventories and project-level activities under the various articles of the protocol. For project-level activities such as reforestation/afforestation, setting such a precision level could encourage project developers to measure projects more precisely if the price of carbon was high. For example, if the total average carbon benefit was 1 million t C with a ±30% confidence interval, this example would result in a lower bound of 0.7 million t C. If forestry projects could only claim benefits for a lower bound of the confidence interval and if carbon was worth $10/t C, this would represent a "loss" of carbon benefits of 0.3 million t, equivalent to $3 million, a value likely to greatly exceed the cost of measuring to a ± 5% precision level (Boscolo et al., 2000). Thus, it is likely that project developers would choose high precision levels for their measurements. A similar argument could be made for national inventories where the motivation for improving their precision would likely be related to the level of compliance on targets.

4. The future role of remote sensing in measuring carbon in forests

Remote sensing data may provide a useful means for measuring carbon stocks in forests, and a range of remote data collection technologies are now available including satellite imagery to aerial photo-imagery from low flying airplanes. To improve the ability of remotely sensing biomass, sensors that can measure the height of the canopy or vertical structure will be needed along with the more traditional sensors on Landsat or Spot satellites. A promising advance in remote measurements of forest biomass carbon is a scanning lidar (a pulsed laser), a relatively new type of sensor that explicitly measures canopy height. NASA planned to include this sensor in one of its Earth System Science Pathfinder program missions (the Vegetation Canopy Lidar Mission—VCL) (more information at: http://www.inform.umd.edu/geog/vcl); however, as of mid 2001, this sensor has not been included in a mission. The VCL Mission would collect data from 25-m wide footprints continuously over land between 67° N and S and would provide three measures: canopy top height, vertical distribution of canopy elements, and surface topography below the vegetation canopy. This sensor would be able to monitor 98% of the earth's closed canopy forests. To date, variations of the airborne lidar have been tested over several forest types and the tests have shown its ability to successfully measure canopy height for conifer forests of the Pacific Northwest USA (Means et al., 1999), deciduous forests in Maryland, USA (Lefsky et al., 1999), and various aged secondary and mature tropical forests in Costa Rica (B. Peterson and J. B. Drake, University of Maryland 1999, personal communication). In the conifer forests of the Pacific Northwest, very high correlations were obtained with the sensor data and height, basal area, and total biomass (Means et al., 1999).

Another promising advance in the remote sensing area, especially at smaller scales such as US counties or project-level activities, couples dual-camera digital videos (wide-angle and zoom) with a pulse laser profiler, data recorders, and differential GPS (geographical positioning system) mounted on a single engine plane [Slaymaker et al., 1999; Electric Power Research Institute (EPRI), 2000]. The plane flies aerial transects across the area at a fixed low altitude, capturing 200-m wide georeferenced strips and a resolution of 50 cm with the wide-angle camera, and a 20-m wide georeferenced strips and a 3-cm resolution with the zoom camera. The plane also flies at higher altitudes to collect stereo images; these images are used to create 3D models of the terrain. From analysis of these two sets of data, this system is able to produce tree crown area, tree height (from the pulse laser), crown density, number of stems per unit area; a combination of which has been shown to correlate highly with aboveground biomass of both complex tropical forests and eastern US hardwood forests. This type of system will be especially useful for measuring carbon in forests being harvested and for monitoring for small-scale human disturbance in protected forests as the presence and extent of forest gaps can readily be observed.

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