Biomass Estimation for Temperate Broadleaf Forests of the United States Using Inventory Data

Paul Schroeder, Sandra Brown, Jiangming Mo, Richard Birdsey, and Chris Cieszewski

ABSTRACT. A potentially valuable data source for estimating forest biomass is forest volume inventory data that are widely collected and available throughout the world. In this paper we present a general methodology for using such data to reliably estimate aboveground biomass density (AGBD) and to develop expansion factors for converting volume directly to AGBD from USDA Forest Service Forest Inventory and Analysis (FIA) data. Growing stock volume inventory data and stand tables were combined with independently developed biomass regression equations to estimate AGBD and to calculate biomass expansion factors (BEF: factors that convert volume to mass, accounting for noncommercial components) for the extensive oak-hickory and maple-beech-birch forest types of the eastern United States. Estimated aboveground biomass for both forest types ranged between 28 and 200 Mg ha^{-1}. Expansion factors decreased from more than 4.0 at low growing stock volume to nearly 1.0 when growing stock volume was as high as 190 m^3 ha^{-1}, consistent with theoretical expectations. In stands with low AGBD (< 50 Mg ha^{-1}), small diameter trees (< 10 cm diameter) contained up to 75% of the AGBD in trees ≥ 10 cm diameter; this proportion dropped to < 10% for stands with AGBD > 175 Mg ha^{-1}. The similarity of our results for two major forest types suggests that they may be generally applicable for estimating AGBD from inventory data for other temperate broadleaf forests. Further, the pattern between BEF and stand volume was similar to that obtained for tropical broadleaf forests, except that tropical forests generally had larger BEFs than temperate forests at a given volume. The implications of these results suggest that a recent assessment of forest biomass in developed countries is too low. For. Sci.: 43(32):424–434.

Additional Key Words: Forest biomass, expansion factors, forest inventory, global carbon cycle.

FOREST VEGETATION REPRESENTS a major pool in the global carbon (C) cycle. Forest vegetation alone contains over 350 Pg C (Dixon et al. 1994) that is subject to decrease or increase as a result of disturbance, harvest, regrowth, or conversion to other land uses, with resulting changes in C fluxes to the atmosphere. The uncertainty surrounding the estimated pool, however, is large because of the uncertainty in biomass density estimates of the world's forests. There is an increasing need to improve the accuracy of forest biomass estimates for several reasons. One of the major provisions of the UN Framework Convention on Climate Change (UNFCC) (United Nations 1992) is that each ratifying country agrees to conduct a "national inventory of anthropogenic emissions by sources and removals by sinks of

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all greenhouse gases not controlled by the Montreal Protocol." Biomass-C densities (expressed as mass per unit area, e.g., Mg ha^{-1}) for different forest types by country will be important components of these assessments.

In addition to making estimates of C pools in forests, estimation of biomass is relevant for studying other global biogeochemical cycles, such as nitrogen, because the amount of a nutrient element in forests is also related to the quantity of biomass present. The quantity of biomass in a forest is the result of the difference between production through photosynthesis and consumption through respiration, mortality, harvest processes, and herbivory. Changes in forest biomass density are brought about by natural succession, human activities such as silviculture, harvesting and degradation, and natural impacts caused by wildfire and climate change. Thus biomass density is a useful measure for assessing changes in forest structure. Biomass density is also a useful variable for comparing structural and functional attributes of forest ecosystems across a wide range of environmental conditions.

It is clear that estimates of biomass densities for forests provide valuable information for many global issues. However, estimating this quantity at suitable scales is not without its problems. The use of remote sensing techniques has been investigated, but as yet this approach has met with little success for multi-age, multi-species forests (e.g., Sader 1988, Nelson et al. 1988) and only with limited success in forests with few species and age classes representing a broad range of biomass distributions (Wu and Strahler 1994, Hall et al. 1995). Even if remote sensing data were shown to be useful for estimating biomass density of forests, ground data at landscape scales would still be needed for calibration and ground truthing because remote sensing techniques do not measure biomass, but rather they measure some other forest characteristic (e.g., crown reflectivity or brightness).

Intensive ecological studies have also been used to quantify biomass density, but they are not conducted at the broad spatial scale needed for national assessments. Instead, they tend to measure biomass on a few small plots (often < 0.1 ha), generally nonrandomly selected. We believe that the best approach for estimating aboveground forest biomass on a national or regional scale is to use data from national forest inventories. This is an appropriate method for broad scale studies because inventory data are generally collected at a landscape scale from the population of interest, the regional forest resource, and are designed to be statistically valid. Such data are also plentiful and are collected by many countries. However, recompilation and reanalysis of original tree and plot-level field data is often impractical because of problems related to data retrieval and the sheer size of the task. It may be more efficient to make use of more readily available forest volume estimates that are derived from the field data and summarized on regional scales. Forest volume inventories have provided the basis for several regional and national-level C budgets (Birdsey 1992, Kolchugina and Vinson 1995, Kauppi et al. 1992, Kurtz and Apps 1993, Turner et al. 1995).

Forest volume inventories, however, do not characterize all forest biomass; they emphasize only the commercially valuable wood. To use volume data to estimate aboveground biomass density (AGBD, defined as aboveground biomass in trees per unit area), it is necessary to develop biomass expansion factors (BEF) that convert volume to mass, and account for noncommercial components such as branches, twigs, bark, stumps, foliage, and seedlings and saplings

Inventory data have been used extensively for estimating the AGBD of tropical forests (Brown et al. 1989, 1991, Brown and Lugo 1992). These studies showed that the BEF was variable over most of the range of inventoried stand volume. For a pan-tropical forest sample, BEF decreased as inventoried volume increased (Brown et al. 1989, Brown and Lugo 1992). Continuous regression functions were developed to estimate BEF for any size (i.e., volume density) of forest.

Inventory data have also been used to estimate regional BEFs for the forests of Virginia [Johnson and Sharpe (1983)]. They also found that BEF (in this case including roots and litter) decreased for larger stand size classes, but they did not calculate a BEF function. The study by Birdsey (1992) on the C budget of U.S. forests [based on the national biomass inventory of Cost et al. (1990)] used discrete BEFs to estimate AGBD.

Most countries in the temperate and boreal zones inventory the standing volume of their forests, albeit to several different standards. These were recently summarized as part of the Forest Resources Assessment 1990 Project (FAO/ECE 1992). Biomass estimates based on these volumes were also reported, but not all aboveground components appeared to be included, thus the estimates among countries are not comparable. Part of the reason for this lack of reporting of total AGBD is the absence of a systematic method to convert inventoried volume to aboveground biomass. For instance, the estimates of the C pools and sinks for temperate European forests (Kauppi et al. 1992) were developed from reliable inventory data, but BEFs to estimate the biomass of forest components were based on approximations from limited studies of both temperate and tropical forests.

Biomass expansion factors are also useful for analyzing the effects of forest harvesting on forest C budgets. Regional and national level harvest data are very often reported in terms of log volume removed. However, the noncommercial components, or slash, are often left behind in the forest to decay or are used for other purposes such as fuelwood. To do a complete accounting of the C releases during harvesting, it is necessary to estimate the biomass C in slash. To account for C in slash, it is necessary to back calculate from the volume data, and BEFs are useful for this step.

The temperate zone studies demonstrate the need for a more reliable methodology to estimate forest biomass from relatively plentiful and available sources of volume inventory data. The main goal of this paper is to investigate whether the forest inventory database for U.S. forests can be used to develop a general methodology for converting inventoried volume of temperate forests to AGBD estimates, as has been done for the tropics. Th ogy is to satisfy immediate needs to undertake regional and national-level analyses under the UNFCC and because of constraints associated with using summary or aggregated data which may have lost some of the detail contained in the raw data. Our intent was to use the extensive U.S. database to both develop a methodology and to investigate trends and patterns that other countries should consider in their own biomass assessments from volume inventories.

We also wanted to improve on earlier methodologies that first converted stem volume to stem biomass and then applied an expansion factor to estimate other aboveground components. The intermediate step of estimating stem biomass from volume and wood density adds error that we hoped to avoid by developing a means to convert volume inventory data directly to AGBD. Because of potential problems with propagation of errors, not only in our study, but also in broader national level assessments, we think this will be an improvement. We continue to use the term BEF, but we redefine it here to be the ratio of AGBD to growing stock volume.

The specific objectives were (1) to determine AGBD from inventory data for two of the most extensive temperate broadleaf forest types of the United States, oak-hickory and maple-beech-birch, using the approach developed by Brown et al. (1989) and Brown and Lugo (1992) for tropical forests and (2) to investigate whether BEFs for temperate broadleaf forests vary with a measure of the stand size/structure. We hypothesized that the BEFs of temperate forests will vary with stand size, i.e., with the inventoried volume, in a manner similar to tropical forests. As the forest inventory data for the U.S. forests included data for trees in smaller size classes (2.54 cm to 10 cm diameter) that are often not reported elsewhere, our third objective was to use these data to determine if a reliable relationship could be developed between the AGBD of trees above and below 10 cm diameter. Many forest inventories for other temperate countries generally report data only for trees with diameters larger than 10 cm and they may be missing a significant quantity of AGBD in the smaller size classes of these often recovering forests (e.g., European forests; Kauppi et al. 1992). We conclude with a discussion that compares the range in BEFs and the relationships between BEF and stand size for temperate forests with those obtained for tropical forests.

Methods

Our overall approach was first to develop biomass regression equations by pooling data from numerous hardwood and conifer species; these were used to estimate oven-dry tree biomass from diameter at breast height (1.37 m above ground level). The equations were then applied to stand tables (number of trees ha^{-1} by diameter class) for USDA Forest Service Forest Inventory and Analysis (FIA) units to estimate AGBD (Mg ha^{-1}) for the oak-hickory and maple-beech-birch forest types. The FIA data also included inventoried growing stock volume by diameter class which was used to calculate BEF, the ratio of AGBD to growing stock volume.

Development of Biomass Regression Equations

There are a plethora of studies that report regression equations for estimating the biomass of eastern hardwood tree species (e.g., Wiant et al. 1977, Montieth 1979, and several sources footnoted in Table 1). For several reasons, however, we chose not to use these regressions. First, the main objective of this study was to determine if a general approach to estimating AGBD could be developed using aggregated forest data. Second, their sample tree data were geographically limited, while our two forest types cover most of the eastern United States. Third, the diameter range for which these equations were appropriate were generally too limited. For example; Wiant et al. (1977) included sample trees up to 41 cm, and Montieth (1979) presents results up to 55 cm diameter. Our volume inventory database (described below) contained significant numbers of trees beyond these ranges, including some individuals in excess of 100 cm diameter. Fourth, biomass data are simply not available for all species in the eastern hardwood forest, so general equations would still need to be developed for unrepresented species. For these reasons, we chose to develop new regression equations, as described next.

Data were assembled from 12 published and unpublished studies of aboveground tree biomass of eastern U.S. forests. Diameter, total height in most cases, and aboveground oven-dry biomass (stem, stump, branch, twig, bark, foliage) for 454 trees of 34 hardwood species of the eastern United States and 83 trees of 5 conifer species were included. The major species groups in the hardwood data were maple (108 trees), oak (97 trees), beech (61 trees), and birch (47 trees). The conifer data contained pine (43 trees), spruce (30 trees), and fir (10 trees). In all studies, sample trees were selected to represent a wide range of tree diameters. For hardwood species, the range in diameter was 1.3–85.1 cm with a mean of 21.6 cm. Conifer species

Table 1. Regression equations (untransformed) developed to estimate oven-dry tree biomass (kg) from tree diameter (cm). For hardwoods, 25000 and 0.5 are chosen constants representing a maximum asymptotic biomass per tree and an intercept or minimum biomass, respectively. The exponent, 2.5, is also a constant in the hardwood equation. The other number is an estimated model coefficient. For conifers, 15000 and 0.5 are also constants and the other two numbers, including the exponent, are estimated coefficients.

Hardwoods*	
$\text{Biomass} = 0.5 + \dfrac{25{,}000 dbh^{2.5}}{dbh^{2.5} + 246{,}872}$	$R^2 = 0.99$ $n = 454$ Min. diameter = 1.3 cm Max. diameter = 85.1 cm Mean diameter = 21.6 cm
Conifers+	
$\text{Biomass} = 0.5 + \dfrac{15{,}000 dbh^{2.7}}{dbh^{2.7} + 364{,}946}$	$R^2 = 0.98$ $n = 83$ Min. diameter = 2.52 cm Max. diameter = 71.6 cm Mean diameter = 19.8 cm

* Sources: J. Chapman 1994, unpublished data; Clark and Schroeder 1977; Clark et al. 1980a, b, c; Crow 1977; Siccama 1993, unpublished data; Sollins and Anderson 1971; Wartluft 1977; Whittaker and Woodwell 1968.

\+ Sources: Clark and Taras 1976; Saucier and Boyd 1982; Sollins and Anderson 1971; Whittaker and Woodwell 1968.

had a diameter range of 2.5–71.6 cm and a mean of 19.8 cm. All trees were sampled from fully stocked stands. Standard destructive sampling methods were used to determine aboveground biomass for each sample tree.

We pooled all of the hardwood species into one data set and all of the conifer species into a second data set for a number of reasons. First, we needed to develop regression equations that were general (as opposed to species specific) and that could be applied to forest inventory data that was classified by forest type (e.g., temperate deciduous hardwoods) but otherwise lacked species information. Second, initial inspection of the data showed that they appeared to be compatible and had no obvious outliers. A similar pooled data approach was used successfully for tropical tree species in the study by Brown et al. (1989). Third, for 23 of 34 hardwood species, the sample size was less than 10 trees spanning a limited diameter range, an insufficient number, we believe, for developing significant regression equations with high coefficients of determination.

We evaluated a variety of regression models commonly used for biomass data (biomass data for hardwood species are shown in Figure 1) on the basis of prediction errors, residual analysis, logical behavior of the models, R^2, and simplicity of the models. Because errors associated with the final regression model would be propagated in computations of AGBD and BEF, strong emphasis was placed on developing a model with good fit and with a small standard error based on symmetrical normally distributed residuals that had no bias or evident trends. Although both height and diameter data were available for biomass prediction, initial analysis showed that only diameter was necessary. Height did not significantly improve models based on diameter alone.

Several linear and nonlinear models were fitted to direct and log-transformed data. As the conditional variance of tree biomass increases with tree size, regressions on the log-transformed data were preferred because they corrected this heterogeneous conditional variance. While the log-transformation stabilized the variance and linearized some models, it did not completely remove the curvature of the underlying model. Some curvilinear equations, therefore, had to be examined even when working with the log-transformed data. These included various polynomials, exponential functions, and fractional functions. Simple linear models for the log-transformed data lacked the curvature necessary to describe the data well and had larger standard errors and asymmetrical residuals with a detectable trend over the range of tree diameter.

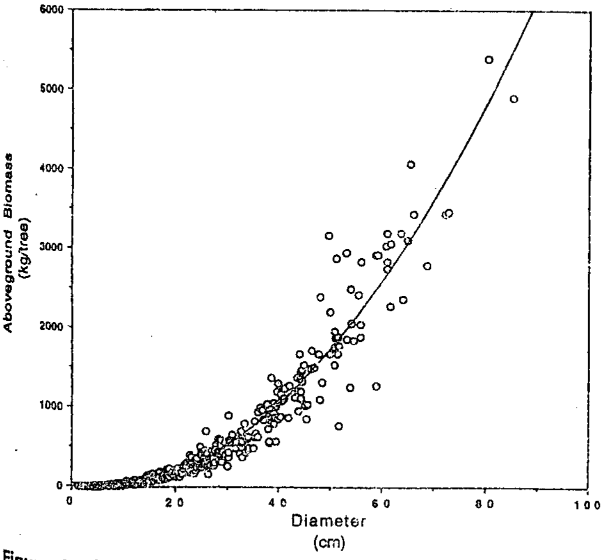

Figure 1. Individual tree data used to develop the biomasss regression equation for hardwood species shown in Table 1.

Log-transformed, nonlinear half-saturation functions (Cieszewski and Bella 1989) were selected as the final models for both hardwoods and conifers (Table 1). In addition to logical behavior, they also had the smallest standard errors, highest adjusted R^2, and best distributed residuals. Despite our pooling of data by species, the resulting regression equations accounted for 99% of the variation in the biomass data. With an additive standard error of 0.264 of the natural log of biomass, the biomass multiplicative error of prediction in the untransformed model was estimated as ranging from –20% to +33%. Although this level of error may seem large, we believe that it actually reflects real variability in nature. Natural variation, especially, increases when many large diameter trees are included, as we did here. A larger sample size might improve the regression relationship, but because of the variability inherent in large trees, it may not be practically feasible to reduce this level of error even with an extremely large sample size.

Forest Inventory Data

Data were extracted from the forest inventory database maintained by the USDA Forest Service for the eastern United States (Hansen et al. 1992). The database contains information from inventories of forest resources conducted on a cycle of approximately 10 yr. The basic design of the eastern inventory is double sampling for stratification (Birdsey and Schreuder 1992). The first phase of the sample consists of a large number of sample points located on aerial photographs and classified according to land cover. The second sample phase consists of a selected subset of the photo sample points that are visited in the field for direct observation and measurement. Each field sample plot is assigned an area weight based on the stratification scheme, probability of selection, and the total sample area, usually a county or an inventory unit (group of counties). Many of the same field plot locations are remeasured periodically to provide a basis for estimating trends.

At each field sample location, trees are selected for measurement using a cluster of sample plots designed to represent 0.4 ha of forest. Individual trees are identified, their diameter measured (minimum diameter of 2.54 cm), and plot area attributes are noted. Growing stock volume for each sample tree with diameter greater than or equal to 12.7 cm is estimated during data compilation using volume regression equations developed for the population being measured (Birdsey and Schreuder 1992). Individual tree estimates are summed on an area basis for the whole plot. No estimate of the error associated with this step has been made by the Forest Service. It is most likely less than the error associated with AGBD because branches, twigs, etc. are not included, but it is likely > 10%.

The plot area is also classified by forest type, stand size class, stand age, stocking, and other defined categories based on measured tree variables. All plots in the sample are aggregated to provide estimates for the entire sample area, or may be aggregated for any subclassification within the sample area using post-stratification methods. The sampling error associated with FIA surveys are typically < 2% at the state level (various USDA Forest Service publications, e.g., Alerich and Drake 1995).

In this study, tree-level data were aggregated to the level of the inventory unit, and independent estimates of volume and AGBD for a diameter class distribution for each of the two forest types were derived. For each 5 cm diameter class, beginning with a lower limit of 2.54 cm, we assembled tables that included the number of live trees. Net growing stock volume, defined as under bark volume of main stem to a 10 cm top for trees 12.7 cm diameter and larger, excluding deductions for both rotten and sound cull, was also given.

Forest type is a plot-level classification defined by the relative stocking of tree species or species groups (Powell et al. 1993). Two populations, defined by forest type, formed the basis for this study. The oak-hickory (*Quercus* spp.–*Carya* spp.) forest type is defined as forests in which upland oaks, singly or in combination, comprise a plurality of the stocking. Common associated species include yellow poplar *(Liriodendron tulipifera)*, elm (*Ulmus* spp.), maple (*Acer* spp.), and black walnut (*Juglans nigra*). Pines may also occur, but at stocking levels < 25%. Oak-hickory is the most extensive forest type in the eastern United States, occupying 51 million ha of land or about one-third of the total area of eastern forests. For this analysis we selected sample plots classified as oak-hickory from the approximate center of its geographical range, as defined by the state boundaries of Indiana, Kentucky, Maryland, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia.

The maple-beech-birch forest type is defined as forests in which maple (*Acer* spp.), American beech (*Fagus grandifolia*), or yellow birch (*Betula alleghaniensis*), singly or in combination, comprise a plurality of the stocking. Common associates include eastern hemlock (*Tsuga canadensis*), elm, basswood (*Tilia* spp.), and white pine (*Pinus strobus*). The maple-beech-birch type is the second most common forest type in the eastern United States, occupying 19 million ha primarily to the north of the oak-hickory type. We selected sample plots to represent this forest type from the states of Connecticut, Maine, Massachusetts, New Hampshire, Ohio, Pennsylvania, and Vermont.

The oak-hickory data represented a total of 44 inventory units, and each unit reported results for three stand size classes: sawtimber, poletimber, and seedling/sapling. The maple-beech-birch data were for 27 inventory units also with the same three stand size classes. One of the oak-hickory data sets and four of the maple-beech-birch data sets, however, were derived from very small field samples of less than five plots each. We dropped these data sets from the analysis because of the relatively high uncertainty associated with such small field samples. This resulted in a total of 131 data sets for the oak-hickory forest type and 77 data sets for the maple-beech-birch forest type. Each data set included stem frequency distribution (trees ha^{-1}) and growing stock volume distribution (m^3 ha^{-1}) by diameter class for both hardwoods and conifers.

Estimation of AGBD

We estimated AGBD for each inventory unit by applying our species aggregated tree biomass regression equations to the aggregated FIA stand table data. Basically, aboveground biomass was estimated for a tree with a diameter equal to the midpoint of each diameter class. The biomass of a tree with diameter of the midpoint was then multiplied by the number of trees in each diameter class. Aboveground biomass density for each diameter class was summed for all diameter classes, and for conifers and hardwoods to arrive at AGBD for each inventory unit.

Errors associated with these estimates would be propagated from the biomass regression equations, use of the midpoint of the diameter class, and errors associated with stand table estimates of numbers of trees in each diameter class. We used diameter class midpoints because the classes were narrow (i.e., 5 cm). This resulted in a 5% overestimate of AGBD compared to using individual tree data (M. Hansen, USDA Forest Service, North Central Forest Experiment Station, pers. comm., 1996). Another alternative would have been to use quadratic mean diameter, but the resulting error would have been 10% (M. Hansen, pers. comm.). A small additional source of error is involved in estimating biomass for the largest diameter class which is open ended (i.e., diameter > 124.5 cm). However, only 14 of our 208 units had any representation in this class, and on average they only had 0.046 trees/ha in the largest class, or about 1 tree per 22 ha. Even though the effect of this on our results was negligible, we used the minimum diameter to estimate biomass for this class which introduces the potential for slight underestimate of biomass.

AGBD for Trees < 10 cm in Diameter

As noted above, the FIA database contained information for trees ≥ 2.54 cm diameter. To study AGBD distribution between trees greater than and less than 10 cm in diameter, we needed to produce a dataset that distinguished between these two size classes. This meant separating out the smallest diameter class (2.5–7.4 cm) and partitioning the next smallest diameter class (7.5–12.4 cm) between trees ≥ 10 cm and < 10 cm. Although 10 cm is coincidentally the midpoint of this diameter class, a linear 50% partitioning was not appropriate because these forests tend to be uneven aged and to display the characteristic exponential or inverse J-shaped diameter frequency distribution with large numbers of small trees and decreasing numbers of larger trees. Instead, we patterned a method after Gillespie et al. (1992) and used the ratio of the number of trees in the two smallest diameter classes to divide the number of trees in the second smallest class into two classes: 7.5–10 cm and > 10–12.4 cm. For the newly divided classes we applied the AGBD regression equation to the midpoints of the two new classes.

Calculation of BEF

Biomass expansion factor was calculated simply as the ratio AGBD/growing stock volume. The AGBD was for trees ≥ 2.54 cm diameter, and growing stock volume was, by definition, for trees ≥ 12.7 cm diameter. We calculated this ratio for each of the 131 oak-hickory and 77 maple-beech-birch stand tables. Because the stand table data for each inventory unit were aggregated from a number of field plots distributed over the area of the inventory unit, these BEFs represent regional factors derived from regional samples. Errors associated with these estimates derive from the biomass regression equations, sampling error, and errors related to the volume regression equations used by FIA (see above).

Results

Aboveground Biomass Density

The highest AGBD was almost 200 Mg ha^{-1} and the lowest was about 30 Mg ha^{-1} for both forest types, but the maple-beech-birch data appeared more variable and slightly higher than the oak-hickory for a given growing stock volume (Figure 2). By stand size, the weighted mean AGBD for the oak-hickory was 170 Mg ha^{-1}, 125 Mg ha^{-1}, and 53 Mg ha^{-1} for sawtimber, poletimber, and seedling/sapling size classes, respectively. The corresponding weighted means for the maple-beech-birch forest type were 169 Mg ha^{-1}, 130 Mg ha^{-1}, and 53 Mg ha^{-1} for sawtimber, poletimber, and seedling/sapling, respectively. Significant polynomial relationships between AGBD and growing stock volume for oak-hickory and maple-beech-birch were obtained (Table 2). Equations (1) and (2) were significantly different from each other. The coefficients b_1 and b_2 were significantly different, but not the intercepts.

Although there were statistical differences between the two forest types, the sample sizes were large enough that even very small differences could prove to be statistically significant. To test whether this difference was practically significant and because a Bartlett test showed equal variances, we pooled the data and calculated another regression equation (Table 2). In the mid-range of the data, where the difference between the oak-hickory and maple-beech-birch curves was greatest (i.e., growing stock volume of approximately 40-90 m^3 ha^{-1}), the pooled equation overestimates AGBD for oak by 3–4% and underestimates AGBD for maple by about 8–11%. At higher and lower levels of growing stock volume, the differences in the estimates decreased.

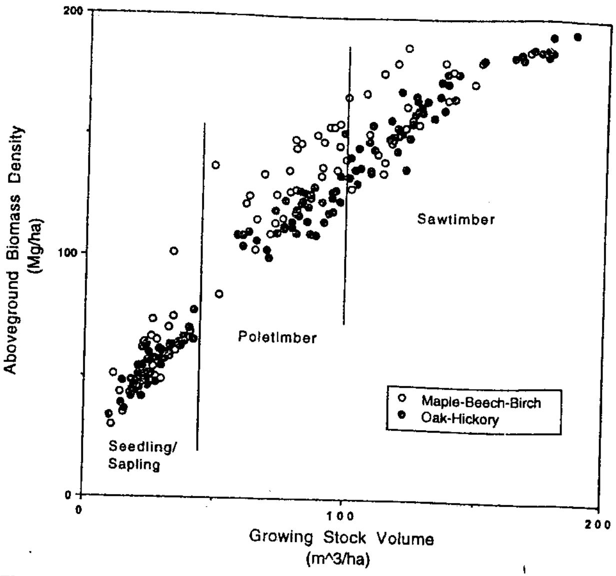

Figure 2. Aboveground biomass density (AGBD) as a function of growing stock volume for oak-hickory and maple-beech-birch forest types, with approximate size class bounds.

Biomass Expansion Factors

Biomass expansion factors decreased with increasing growing stock volume for both oak-hickory and maple-beech-birch forests (Figure 3). For oak-hickory, the highest BEF was about 3.25 and decreased to nearly 1.0. For maple-beech-birch, the highest BEF was about 4.5 and also decreased almost to 1.0. There were no significant differences in the relationship between BEF and growing stock volume for the two forest types, so we pooled the data and calculated a single regression equation:

$$\mathrm{BEF} = \mathrm{EXP}(1.912 - 0.344 * \ln GSV)$$

$R^2 = 0.85$, $n = 208$,

GSV = growing stock volume (m^{3}ha^{-1})

Std. error of estimate = 0.109

The shape of the relationship is consistent with theoretical expectations. At very low growing stock volume, we expect BEF to be high because all trees have some positive biomass, but only trees larger than 12.7 cm diam-

Table 2. Regression coefficients for equations relating aboveground biomass density (AGBD, Mg ha^{-1}) to growing stock volume (GSV, m^3 ha^{-1}) for oak-hickory and maple-beech-birch forest types and for their pooled data. The regression equations are second-order polynomials of the form: $AGBD = b_0 + b_1 GSV + b_2 GSV^2$. SE = standard error of the estimate.

	b_0	b_1	b_2	r^2	n	SE
(1) Oak–hickory	18.925	1.446	–0.003	0.98	131	6.501
(2) Maple–beech–birch	14.033	1.901	–0.005	0.92	77	12.897
(3) Pooled	17.625	1.601	–0.004	0.95	208	10.528

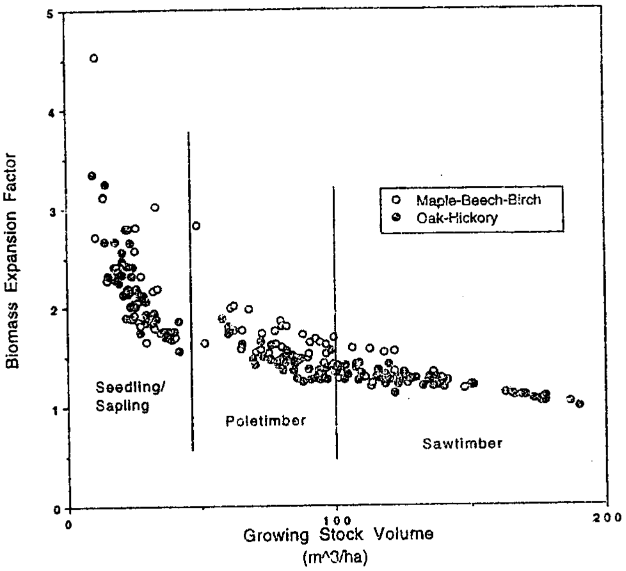

Figure 3. Biomass expansion factor (BEF) as a function of growing stock volume for oak-hickory and maple-beech-birch forest types, with approximate size class bounds. BEF is the ratio of aboveground biomass density (AGBD) to growing stock volume.

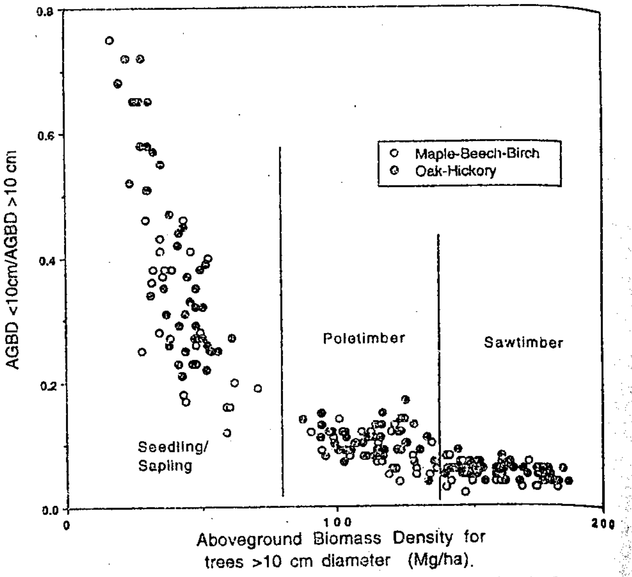

Figure 4. The ratio of aboveground biomass density (AGBD) in trees < 10 cm diameter to biomass of trees ≥ 10 cm diameter as it relates to aboveground biomass density (AGBD) for trees ≥ 10cm diameter, with approximate size class bounds.

eter are defined as having any growing stock volume. The biomass expansion factor approaches infinity as growing stock volume approaches zero and becomes undefined when there is no growing stock volume, as division by zero is undefined. Throughout the range of our data, BEF decreased with increasing growing stock volume. However, we expect the BEF to become constant at high growing stock volumes as was found for tropical forests (Brown and Lugo 1992). This constant value, or theoretical minimum BEF, depends on the partitioning of AGBD into the main stem and other components in very large and dense stands. For example, for a hypothetical stand with all biomass in stems, the BEF would equal the average wood density of the stand. However, if we assume more realistically that 80% of AGBD is contained in the stem component, then the BEF would theoretically equal the product of 1.25 and average wood density of the stand (stem biomass/stem volume = wood density, and if AGBD = 1.25 * stem biomass, then (1.25 * stem biomass)/stem volume = BEF, which is equivalent to 1.25 * wood density = BEF). Common oak and maple species have green volume based wood densities (oven-dry mass/green volume) of 0.49 – 0.60 Mg m^3 (Forest Products Laboratory 1990). Therefore, we would expect minimum BEFs of approximately 0.61 – 0.75.

Biomass in Trees Less Than 10 cm Diameter

The ratio of AGBD in trees < 10 cm diameter to AGBD in trees ≥ 10 cm diameter decreased with increasing AGBD as would be expected (Figure 4). Smaller trees were generally a larger component of AGBD in low biomass stands, e.g., for AGBD < 50 Mg ha^{-1}, small trees contained as much as 75% of the AGBD for all trees ≥ 10 cm diameter. This proportion dropped to < 10% for AGBD > 175 Mg ha^{-1}. Analysis showed that there was no statistical difference in this relationship between oak-hickory and maple-beech-birch, so we pooled the data and computed a single regression equation to estimate the ratio:

$$AGBD_{<10}/AGBD_{\geq 10} = \mathrm{EXP}(3.75 - 1.305 * \ln AGBD_{\geq 10})$$

$R^2 = 0.89$, $n = 208$, $AGBD$ = Mg ha^{-1}

Std. error of estimate = 0.288

Discussion

Verification of a General Approach to Biomass Estimation

As stated at the outset, our main objective was to develop a general method for estimating AGBD from inventories of growing stock volume. A first step in this methodology was to estimate AGBD from USDA Forest Service FIA data and biomass regression equations. Our approach differed in two ways from that of the USDA Forest Service (Cost et al. 1990, Birdsey 1992): our use of two pooled multispecies biomass regression equations versus a variety of species-specific ones and our use of aggregated stand tables versus use of individual tree data. We have shown that the error in our AGBD estimates due to the regression equation is about +33% to –20%, and that bias due to the use of the aggregated stand tables and diameter class midpoints is about +5%. We have no similar information about the uncertainty due to the biomass regression equations used by Cost et al. (1990).

Despite the differences in approaches, our estimates of AGBD were comparable to those obtained by the USDA Forest Service (Table 3). For three regional forest types (Northeast/Mid-Atlantic and Southeast oak-hickory and Northeast/Mid-Atlantic maple-beech-birch), we recalculated weighted mean AGBDs corresponding to the three regional forest types shared by both studies (Table 3). The results in the Birdsey (1992) report, however, were not reported by size

Table 3. Aboveground biomass density (AGBD) estimates for hardwood forests of the eastern United States based on inventory data. Estimates are organized by stand size class (i.e., sawtimber, poletimber, seedling/sapling) or by site productivity class (i.e., high, medium, low).

Forest type	Location	AGBD (Mg ha^{-1})		Source
		Mean	Range	
Maple–beech–birch	Northeast/Mid-Atlantic			This study
Sawtimber		169	125–188	
Poletimber		130	65–154	
Seedling/sap.		53	28–101	
All sizes		138		
Oak–hickory	Northeast/Mid-Atlantic			This study
Sawtimber		165	136–187	
Poletimber		120	99–138	
Seedling/sap.		59	33–77	
All sizes		139		
Oak–hickory	Southeast			This study
Sawtimber		187	182–193	
Poletimber		135	128–146	
Seedling/sap.		46	39–51	
All sizes		146		
Maple–beech–birch	Northeast/Mid-Atlantic			Birdsey 1992
High		105		
Medium		97		
Low		90		
All classes		97		
Oak–hickory	Northeast/Mid-Atlantic			Birdsey 1992
High		112		
Medium		109		
Low		97		
All classes		106		
Oak–hickory	Southeast			Birdsey 1992
High		152		
Medium		98		
Low		71		
All classes		110		
Mixed hardwood	Virginia			Johnson and Sharpe 1983
Sawtimber		143		
Poletimber		101		
Seedling/sap.		34		
All sizes		103		

class (i.e., sawtimber, poletimber, seedling/sapling), but by timber productivity class (i.e., high, medium, low). Therefore, the data in Table 3 are not directly comparable class by class, but are useful for a more general comparison for regions where our data overlap.

Both approaches show that oak-hickory forests in the Southeast had some of the highest AGBD, and, given the level of uncertainty in both studies, were generally comparable. In the Northeast/Mid-Atlantic region, our AGBD estimates tended to be higher for both oak-hickory and maple-beech-birch forest types, although the results reported by Birdsey (1992) were within the range of our data. Again, considering the level of uncertainty involved, and remembering that our size classes and the productivity classes in Birdsey (1992) are not directly equivalent, it appears that our estimates are roughly comparable.

Another inventory-based study conducted on the mixed hardwood forests in Virginia also used a variety of species-specific biomass equations (Johnson and Sharpe 1983). That study reported the biomass of merchantable stand components in the same size classes that we used (Table 3). Once again, their AGBD estimates were within the range of ours for this region across all three size classes.

Considering the errors associated with all of these estimates, we conclude that our estimates of AGBD are basically the same as those reported by others for the same forest types and regions (Table 3). This suggests that general multispecies biomass regression equations used in combination with stand tables of small diameter classes can be a useful way to estimate AGBD of forests. It is probably most appropriate for broad-scale assessments of, for example, comparisons of biomass stocks at regional and national scales, and to estimate C pools and flux in the forest sector.

The above discussion, and the consistency of relationships between AGBD and growing stock volume and between BEF and growing stock volume for two major forest types, suggests that they may be applicable for converting inventoried volume to AGBD for other temperate broadleaf forests. Data are not available for all forests of the United States with the level of detail of FIA data, and BEFs would be needed to convert volume estimates to biomass for these other forestlands. We believe that the relationships between BEF and growing stock volume that we have developed may be used in other forest types because they include the variation of BEF with stand size, rather than the constant BEFs by region given by Birdsey (1992). Although we have analyzed relationships for only two forest types of the United States, we anticipate that other temperate broadleaf forests would exhibit similar patterns. Analysis of additional forest types, however, is necessary to test this hypothesis.

Utility of the $\mathrm{AGBD}_{<10}/\mathrm{AGBD}_{\geq 10}$ *Results*

There was a predictable relationship between the distribution of AGBD in trees greater than and less than 10 cm in diameter that was unrelated to forest type. This seems to indicate that it would be possible to use this relationship to estimate AGBD for the smaller size class trees with other inventory data that only include trees > 10 cm in diameter. It at least provides a basis for assessing the potential importance of omitting the smaller trees. For example, when AGBD is > 150 Mg ha^{-1}, the error introduced by excluding the smaller trees is likely to be < 10% (Figure 4). For forests with AGBD < 80 Mg ha^{-1}, however, omitting the smaller diameter class could introduce a sizable error of up to 40%. As the extent of younger secondary forests appears to be expanding globally, either through abandonment of marginal croplands or regeneration of logged forests, the amount of biomass in trees < 10 cm diameter takes on greater significance in national estimates of C pools and flux.

Implications for Biomass Estimates of the World's Forests

United States

In their assessment of carbon storage and accumulation in U.S. forests, the USDA Forest Service used discrete point estimates of BEFs for oak-hickory and maple-beech-birch forests in the northeast and southeast regions equivalent to 1.08–1.15 (Birdsey 1992). We calculated BEFs for these regional forest types that were weighted by the number of FIA field sample plots in each of the stand size classes (i.e., sawtimber, poletimber, and seedling/sapling). Our assumption was that forests in each region would be distributed in the same proportions among these size classes as the field sample data. Our size class weighted BEFs were 1.37–1.58.

The BEFs used in the USDA Forest Service analysis are within the range that we estimated for sawtimber stands (Figure 3). However, our field plot data set was composed of 40–50% poletimber and seedling/sapling plots with BEFs of 1.33 to 2.35. This demonstrates the importance of recognizing and accounting for the relationship between BEF and stand size (e.g., growing stock volume density) and why it is desirable to develop a continuous function to estimate BEF. If our analysis is correct, the biomass of U.S. forests may represent a larger C pool than previously realized.

Europe

Kauppi et al. (1992) estimated that European forests accumulated 250 × 10^{6} m^{3} yr^{-1} in growing stock over the period 1971–1990. They used BEFs equivalent to 0.6 – 0.8, values which we have shown to be at or below a theoretical limit even if we consider the somewhat different definitions of growing stock that are used for European forests compared to U.S. forests (FAO/ECE 1992). The total aboveground biomass accumulation in all European forests was estimated to be of 140–210 Tg yr^{-1}. In 1980, 37% of European growing stock was in nonconiferous forests with a mean growing stock volume of 120 m^{3} ha^{-1} (FAO/ECE 1986). Based on our analysis, a more appropriate BEF would be 1.3. If we apply this factor to biomass accumulation by all European forests, the result would be 320 Tg yr^{-1}. If we apply it only to the nonconiferous growing stock we would estimate annual biomass accumulation of 118 Tg yr^{-1} which is 50–127% larger than a comparable proportion of the estimates of Kauppi et al. (1992).

Considering all of the potential sources of uncertainty in our analysis, differences in results of 20–25% may or may not be important. However, differences of 50% or more invite further examination. This analysis suggests that temperate broadleaf forests in Europe may represent a larger C pool than previously thought and may also actively store more C annually than indicated by previous results. An expanded analysis of AGBD and BEF for additional forest types would provide valuable tools that could be used in future C budget analyses. We believe that the type of approach described here is preferable to using one or two point estimates of expansion factors because it provides a continuous function for estimating BEF and subsequently AGBD within theoretical limits.

A recent analysis of the state and change of the world's forests estimated their total biomass stock (aboveground) to be 440 Pg (FAO 1995). About 26% of this was estimated to be located in the temperate and boreal zones or in developed countries; the remainder was located in the mostly tropical developing countries. Using the data reported in the FAO report (1995), we calculated a BEF for all forests in developing countries of 1.5 and for developed countries of 0.69. For developing countries, this estimated BEF appears to be reasonable based on the average growing stock of 113 m^{3} ha^{-1} (Figure 5). However, for the developed countries, this estimated BEF at a growing

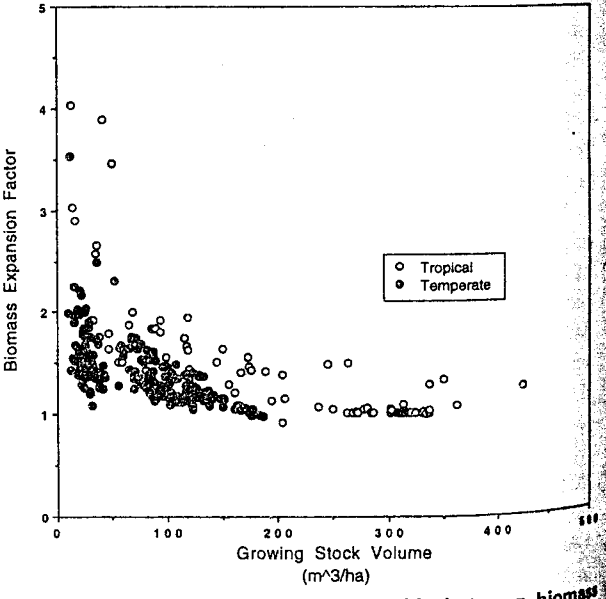

Figure 5. Comparison of the relationship between biomass expansion factor (BEF) and growing stock biomass for temperate and tropical forests.

stock volume of 114 m^3 ha^{-1} is almost half the value projected from Figure 5, or at practically the lower theoretical limit expected for mature forests. Based on the analysis and arguments presented in this paper, we believe that the biomass estimates for forests in developed countries reported in the global assessment do not include all aboveground tree biomass components as is the case for the tropical forests. Further, based on the results in Figure 5, the BEF for temperate forests could be about 1.25 for growing stock volume of 114 m^3 ha^{-1}. This means that temperate and boreal zone forests could contain up to 203 Pg of biomass, or 1.8 times as much as reported in the FAO (1995) report.

Comparison to the Tropics

We compared the relationship between BEF and growing stock volume that we obtained with that for broadleaf forests in tropical America, Asia, and Africa (Brown and Lugo 1992 modified from Brown et al. 1989). These pantropical data were based on biomass and volume estimates for trees with diameter ≥ 10 cm. For comparison, we calculated new BEF for temperate forests by omitting data for temperate trees < 10 cm in diameter. We could not adjust for differences in the definitions of volume, but we expect them to cancel out as the differences work in opposite directions. For example, for the tropics, growing stock volume is defined as volume over bark for trees with minimum diameter ≥ 10 cm. versus volume under bark for trees with minimum diameter ≥ 12.7 cm for the United States. There was some overlap between the two sets of data (Figure 5), but in general the BEFs for the tropical stands were larger than for the temperate stands for a given growing stock volume. This suggests that a tropical forest of a given AGBD has less growing stock volume than a temperate forest of the same AGBD.

A major difference between the tropical and temperate forests was that the former had a much higher maximum growing stock biomass than the temperate forests: over 400 m^3 ha^{-1} compared to about 200 m^3 ha^{-1}. We would also expect that at high values of growing stock volume, BEF for temperate forests would become constant as it does for tropical forests. However, over the range of our data this did not occur. Further, the BEF for tropical forests appears to have leveled at a value of 1.0 at about a growing stock volume of ≥ 250 m^3 ha^{-1}. Assuming an average wood density of tropical trees to be about 0.6 g cm^{-3} (Reyes et al. 1992) and a BEF of one, we estimate that about 60% of the aboveground biomass of mature tropical forests is in the merchantable bole, with the remainder in branches, twigs, and leaves.

Conclusion

Forest volume inventories are a rich source of data that are useful for estimating forest AGBD. They provide a basis for many countries to estimate their forest biomass stocks and C sources and sinks as required by the UN Framework Convention on Climate Change. We demonstrated consistency in the relationship between BEF and growing stock volume for oak-hickory and maple-beech-birch forest types, and also showed that the form of the relationship is the same as has been observed for tropical broadleaf forests. This analysis clearly illustrated the importance of accounting for stand size when estimating BEF. Analysis of additional forest types would help to confirm the generality of this relationship; however, we believe that our analysis is the most comprehensive to date and that our results are applicable to other temperate hardwood forests.

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