A Comparison of Above-Ground Dry-Biomass Estimators for Trees in the Northeastern United States

James A. Westfall

ABSTRACT

In the northeastern United States, both component and total aboveground tree dry-biomass estimates are available from several sources. In this study, comparisons were made among four methods to promote understanding of the similarities and differences in live-tree biomass estimators. The methods use various equations developed from biomass data collected in the United States and Canada. For hardwood species, estimates for biomass components tended to differ among the methods; however, the estimates for total aboveground biomass were more compatible. For softwood species, the biomass estimates among methods were more consistent for components and total aboveground biomass. Considerable variation in biomass component estimates exists among the four methods, suggesting that further study of biomass is needed in the northeastern United States. Ideally, reliable biomass estimators would be established via a regionwide study having consistent and precise definitions and measurement protocols.

Keywords: biomass components, component ratio, forest inventory, tree carbon

The proliferation of renewable bioenergy usage has placed increased emphasis on estimates of current biomass in forests and rates of removals. For example, bioenergy-reliant commercial enterprises and biofuel manufacturing ventures cannot be established unless a sustainable biomass supply can be assured (Galik et al. 2009, Froese et al. 2010). There is further need for biomass availability for heating of homes and other buildings (Lindsay et al. 1992). As the demand on forests as a source of bioenergy is expected to increase in the near future (Benjamin et al. 2010), obtaining accurate estimates of tree biomass is paramount for making sound forest management, economic, and policy decisions.

The seemingly ever-increasing interest in forest biomass has resulted in numerous studies on methods for biomass estimation. Although biomass in forests includes several sources, such as nonwoody vegetation and down woody material, a substantial portion of the forest biomass occurs in standing trees. In the eastern United States, research papers on tree biomass estimation began to flourish in the late 1970s (Wartluft 1977, Wiant et al. 1977, Monteith 1979), with a plethora of research in the early 1980s in the southern (Cost and McClure 1982, Clark et al. 1985), north central (Smith and Brand 1983, Hahn 1984, Smith 1985), and northeastern regions (Young et al. 1980, Tritton and Hornbeck 1982, Wharton et al. 1985). With biomass estimation systems in place for most areas, there was little further work done in the northeastern United States until Wharton and Griffith (1998) developed a system to estimate biomass for various portions (components) of trees using much of the earlier work in the northeastern region. At about this same time, demand was growing for the ability to estimate tree biomass across large geographic areas. Ter-Mikaelian and Korzukhin (1997) assisted by summarizing existing biomass models (of identical form) and their applicable geographic area for 65 tree species in North America. A compendium of biomass equations for North American tree species was compiled by Jenkins et al. (2004). Jenkins et al. (2003) presented biomass equations and component ratios intended for national-scale application in the United States using "pseudo-data" generated from a number of other biomass studies. Similarly, national-scale biomass equations for Canada were developed by Lambert et al. (2005) from biomass data collected nationwide. Heath et al. (2009) expanded on the biomass component ratios of Jenkins et al. (2003) by incorporating these ratios into biomass predictions that were directly linked to sound cubic volume of trees. Thus, biomass estimates were "calibrated" by using local tree volume models.

In the northeastern United States, several methods are available for comprehensive aboveground dry-biomass information, i.e., individual-tree component and total aboveground biomass estimates. These include the regional procedures described by Wharton and Griffith (1998), the volume-adjusted method of Heath et al. (2009), and the national techniques of Jenkins et al. (2003) and Lambert et al. (2005). The lack of a regionwide independent data set makes it impractical to assess which of these methods provides the most accurate estimates. However, a comparison of the biomass estimates obtained from the four methods can help foresters better understand the various methodological approaches to biomass estimation and how the estimates differ depending on the method selected. The purpose of this study was to compare among four methods (1) the ratios to total aboveground tree biomass for various components, (2) the tree-level estimates for pounds of aboveground biomass and

Manuscript received January 7, 2011, accepted September 30, 2011. http://dx.doi.org/10.5849/njaf.11-001.

James A. Westfall (jameswestfall@fs.fed.us), US Forest Service, Forest Inventory and Analysis, Northern Research Station, 11 Campus Boulevard, Suite 200, Newtown Square, PA 19073. *The author is grateful to Paul Van Deusen, Jennifer Jenkins, and three anonymous reviewers for providing comments that improved the manuscript.*

This article uses metric units; the applicable conversion factors are: millimeter (mm): 1 mm = 0.039 in.; centimeters (cm): 1 cm = 0.39 in.; kilograms (kg): 1 kg = 2.2 lb.

This article was written and prepared by a US Government employee on official time, and it is therefore in the public domain and not copyrightable.

Table 1. Mean (with standard deviation), minimum (min.), and maximum (max.) values for dbh (in.), total height (ft), and proportion of rotten/missing cull from 15 species in the northeastern United States.

		dbh (in.)			Total height (ft)			Proportion rotten/missing cull		
Species	No. of trees	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Balsam fir	14,216	7.0 (1.8)	5.0	18.7	41 (11)	10	88	0.01 (0.06)	0	1
Red spruce	11,867	8.3 (2.8)	5.0	25.8	46 (13)	12	109	0.00 (0.03)	0	1
Eastern white pine	11,987	10.8 (5.1)	5.0	40.7	55 (20)	12	141	0.01 (0.05)	0	1
Northern white-cedar	7,055	8.8 (3.0)	5.0	30.1	38 (09)	14	86	0.08 (0.21)	0	1
Eastern hemlock	15,036	9.6 (3.9)	5.0	34.5	45 (16)	10	112	0.01 (0.06)	0	1
Red maple	44,085	8.8 (3.4)	5.0	36.4	56 (14)	10	124	0.05 (0.13)	0	1
Sugar maple	22,021	9.6 (4.1)	5.0	50.0	59 (15)	15	126	0.04 (0.11)	0	1
Yellow birch	8,034	9.4 (4.0)	5.0	38.6	52 (12)	15	103	0.03 (0.12)	0	1
Paper birch	6,626	7.9 (2.5)	5.0	23.7	50 (12)	12	95	0.01 (0.07)	0	1
American beech	11,616	8.6 (3.6)	5.0	36.9	51 (15)	8	140	0.08 (0.19)	0	1
White ash	8,954	9.6 (4.1)	5.0	43.4	61 (18)	16	140	0.02 (0.09)	0	1
Quaking aspen	3,561	8.8 (3.1)	5.0	26.6	58 (13)	20	105	0.03 (0.10)	0	1
Black Cherry	9,320	9.7 (4.0)	5.0	33.1	57 (17)	11	130	0.03 (0.11)	0	1
White Oak	6,246	10.9 (4.6)	5.0	43.2	61 (18)	16	128	0.01 (0.06)	0	1
Northern red oak	9,895	11.7 (5.1)	5.0	47.5	63 (16)	12	140	0.01 (0.07)	0	1

its components, and (3) the per-acre estimates for pounds of aboveground biomass and its components.

Data

The data used in this study were obtained from the Forest Inventory and Analysis (FIA) program of the US Forest Service across 13 states in the northeastern United States (West Virginia, Maryland, Delaware, New Jersey, Pennsylvania, Ohio, New York, Massachusetts, Rhode Island, Connecticut, Vermont, New Hampshire, and Maine). The data were collected from 2002 to 2006 using the sampling and plot designs used nationally by FIA (Reams et al. 2005). Although the FIA program collects data at numerous levels of detail, the individual-tree data for trees having dbh of 5.0 in. and larger are of primary interest for this analysis. To facilitate computations across various biomass estimators, the data were limited to 15 commercial tree species (Table 1). These species comprised 73% of the number of sampled trees. There were five tree variables needed: dbh, total tree height, species, proportion of cubic cull, and proportion of rotten/missing cubic cull in the merchantable stem (1 ft to merchantable height at 4-in. top diameter). The dbh, total tree height, and species were needed to calculate gross biomass, and the cull information was used in computations of net merchantable stem biomass and sound cubic-foot volume. Note that proportion of rotten/missing cull equal to 1 implies a dead tree. A summary of pertinent data characteristics is given in Table 1.

Methods

Four approaches to estimation of tree dry-biomass were identified as being applicable to the northeastern United States. The first approach was used by FIA beginning in the mid-1990s (Wharton and Griffith 1998). These methods, hereafter specified as the northeastern method (NE), used three equations from various independent studies to estimate total aboveground biomass (AGB) estimates. These equations were published by Young et al. (1980) (Equation 1), Wiant et al. (1977) (Equation 2), and Monteith (1979) (Equation 3):

$$\ln(Y_{\mathrm{lb}}) = \beta_0 + \beta_1 D_{\mathrm{in}} + e \tag{1}$$

$$\log_{10}(Y_{\mathrm{lb}}) = \log_{10}\beta_0 + \beta_1 \log_{10} D_{\mathrm{in}} + e \tag{2}$$

$$Y_{\mathrm{kg}} = \beta_0 + \beta_1 D_{\mathrm{mm}} + \beta_2 D_{\mathrm{mm}}^2 + e \tag{3}$$

where Y_{lb} is the AGB weight in lb, Y_{kg} is the AGB weight in kg, D_{in} is dbh in in., D_{mm} is dbh in mm, ln is natural logarithm, $\log_{10}$ is base 10 logarithm, β_i values are estimated parameters, and e is random error. These equations covered 21 key species, with other species being assigned to an equation based on similarities in dry-weight densities. Proportions of AGB occurring in the stump, branch, and foliage components were determined from information given in Young et al. (1980).

The second approach was a set of biomass equations presented by Jenkins et al. (2003), which were intended for application at a national scale in the United States (US method). A common model form was used for four hardwood species groups and five softwood species groups:

$$Y_{\mathrm{kg}} = \exp(\beta_0 + \beta_1 \ln(D_{\mathrm{cm}})) + e \tag{4}$$

where D_{cm} is dbh in cm, exp is exponential function, and other terms are as defined above. Partitioning of AGB into foliage, stem bark, and stem wood components was accomplished by application of ratios (based on hardwood/softwood classification) determined from the following equation:

$$R = \exp\left(\beta_0 + \frac{\beta_1}{D_{\mathrm{cm}}}\right) + e \tag{5}$$

where R = ratio of component weight to AGB, and other terms are as defined above. Although ratios for the stump component are explicitly provided, stump biomass computations were performed using Raile's (1982) models along with specific gravity information (Jenkins et al. 2003).

A third approach was developed by Heath et al. (2009), where the merchantable bole biomass estimate was derived from the sound tree volume predicted using the standard FIA methods applicable to a specific state/region. The steps for computation are as follows: (1) convert the sound volume of wood in the merchantable bole to biomass using specific gravity, (2) calculate the biomass of bark on the merchantable bole using percentage bark and bark specific gravity, (3) calculate the biomass of tops and limbs as a proportion of the bole biomass based on component proportions from Jenkins et al. (2003), and (4) calculate the biomass of the stump based on equations in Raile (1982) (Heath et al. 2009). Note that this method, as published, does not include the foliage component as part of AGB. This strategy is designated the component ratio (CR) method.

The fourth method was implementation of the equations developed for national application across Canada (Lambert et al. 2005). These species-specific equations were developed from biomass data collected across Canada; however, the results were heavily influenced by data from Ontario and Quebec (geographically proximal to the northeastern United States).

Separate equations are used to predict the biomass in wood, bark, branch, and foliage components; however, the model form is the same for each:

$$Y_{\text{kg}} = \beta_0 D_{\text{cm}}^{\beta_1} H^{\beta_2} + e \tag{6}$$

where H is tree height (m), and other terms are as defined above.

Unlike the other methods, the Canadian (CAN) technique uses both dbh and tree height as predictors. AGB is computed as the sum of all components.

To make valid comparisons, a consistent set of definitions applicable across all methods was needed. Particularly, specific portions of the tree for which biomass estimates are desired need to be defined. For this study, these components were (1) stump (S), (2) net merchantable bole including bark (B), (3) top/limbs (T), and (4) foliage (F). AGB was defined as S + B + T + F. To facilitate comparisons, the proportion of AGB contained in each component was calculated. For the CR method, computation of AGB for this study was accomplished by including foliage biomass (F) that was specifically excluded from AGB by Heath et al. (2009). The estimate of F is derived from the foliage ratio given in Jenkins et al. (2003).

For the US method, models for AGB and for the ratios of component biomass to AGB were explicitly given for the foliage (excluding twigs) and merchantable bole wood and bark portions. Thus, component ratios for the stump and top/limbs were needed. Recall that stump biomass was computed on the basis of Raile (1982). The biomass in tops/limbs was the additional amount required to have the entire component biomass sum to AGB; that is, tops/limbs biomass was found by difference. Ratios for each component were calculated by dividing component biomass by AGB.

The NE method provides component biomass for roots/stump, net merchantable stem, top/limbs, and foliage (excluding twigs) (Wharton and Griffith 1998). For this study, separation of root and stump biomass is needed. Using the taper equations described by Westfall and Scott (2010), cubic volumes of stump (1 ft stump height) and merchantable bole (1 ft to merchantable height at 4-in. top diameter) were calculated. The merchantable bole volume was divided by its biomass to obtain an estimate of pounds of biomass per cubic foot of volume. This weight-per-volume unit was used in conjunction with the stump volume to estimate stump biomass. Each component biomass was divided by AGB to obtain component ratios.

The biomass models for the CAN method (Lambert et al. 2005) allow for computation of AGB as the sum of all the biomass components; however, the components directly predicted from the models are stem wood (base to tip), stem bark (base to tip), branches, and foliage (including twigs). To consider the desired biomass components, the stem wood/bark needed to be separated into stump, net merchantable stem, and top. This separation provides two of the three needed components, and the tops/limbs component is obtained by summing the top and branch portions. Volume ratios were used to portion the stem biomass into the three sections. Using taper equations (Westfall and Scott 2010), gross cubic stem volume was obtained, as well as cubic volumes of stump (1 ft stump height), merchantable bole (1ft to merchantable height at 4-in. top diameter), and top (height at 4-in. top diameter to tip). The proportion of total stem volume for each of these sections was computed. It was assumed that biomass is similarly distributed (disregarding within-tree density changes), so these values were used as the biomass component ratios for the stump, net merchantable stem, and top. No attempt was made to separate the foliage component into leaves and twigs. As such, the CAN method is expected to have relatively small T and large F ratios.

Understanding how the four approaches differ in terms of within-tree biomass estimates and ratios is important; however, the methods also need to be evaluated from a forest inventory perspective. To mimic commonly reported FIA statistics (i.e., state-level estimates), a subset of the data (New York) containing all species of interest was used. Mean per-acre estimates and associated 95% confidence intervals were calculated using the procedures described by Van Deusen (2004). As a proxy to formal hypothesis testing, estimates were considered to be statistically different if there was no overlap in confidence interval range.

Results and Discussion

Component Ratios

The trend for stump biomass ratios is to decrease with increasing tree size. For hardwood species, the ratios of stump biomass to AGB for all four methods ranged from roughly 0.03 to 0.07 (Figure 1). The S ratios for the NE models were the largest among the methods, where stump biomass comprised 0.06 to 0.07 of AGB. The hardwood S ratios for the NE method also had inconsistent patterns in relation to tree size; that is, they initially decreased with increasing dbh but then began to increase again. In contrast, the S ratios were more consistent for softwood species, where ratios decreased with increasing dbh (Figure 2). The NE method had the highest ratios for softwoods across all diameter classes, whereas the US method had the smallest softwood ratios.

Generally, the B ratios increased with increasing diameter; yet there were considerable differences between some of the methods. Because of the inherent linkage between US and CR ratios, the B ratios were identical for these two methods. For hardwood species, US/CR indicated the smaller trees had a B ratio of about 0.63, and the largest trees had nearly 0.80 of the AGB in the B portion (Figure 1). The NE models differed substantially from US/CR for smaller hardwood trees but were in close agreement for the upper diameter classes. The B ratios for hardwood species from the CAN models were considerably smaller than the other three methods. The ratio peaked at nearly 0.66 for trees having dbh of roughly 14 in. Thereafter, the ratios began to decrease with increasing dbh, primarily because of increases in the F ratio for larger trees (Figure 1). For softwood species, there was much less variation in B ratio by dbh class (Figure 2). The US/CR ratios were 0.73 to 0.79 across the range of tree sizes. The B ratio for softwoods under the NE method was about 0.04 less than US/CR. The CAN method produced softwood B ratios that were notably smaller and more variable than the other three methods.

The proportion of AGB composed of top/limbs biomass was also quite consistent between US and CR. The T ratios for hardwood species decreased from nearly 0.29 for small dbh trees to approximately 0.15 for the largest dbh trees (Figure 1). The T ratios for hardwood species given by the NE methodology were essentially independent of tree size (~0.10). The CAN T ratios for hardwoods exhibited a range of variability with tree size similar to US and CR

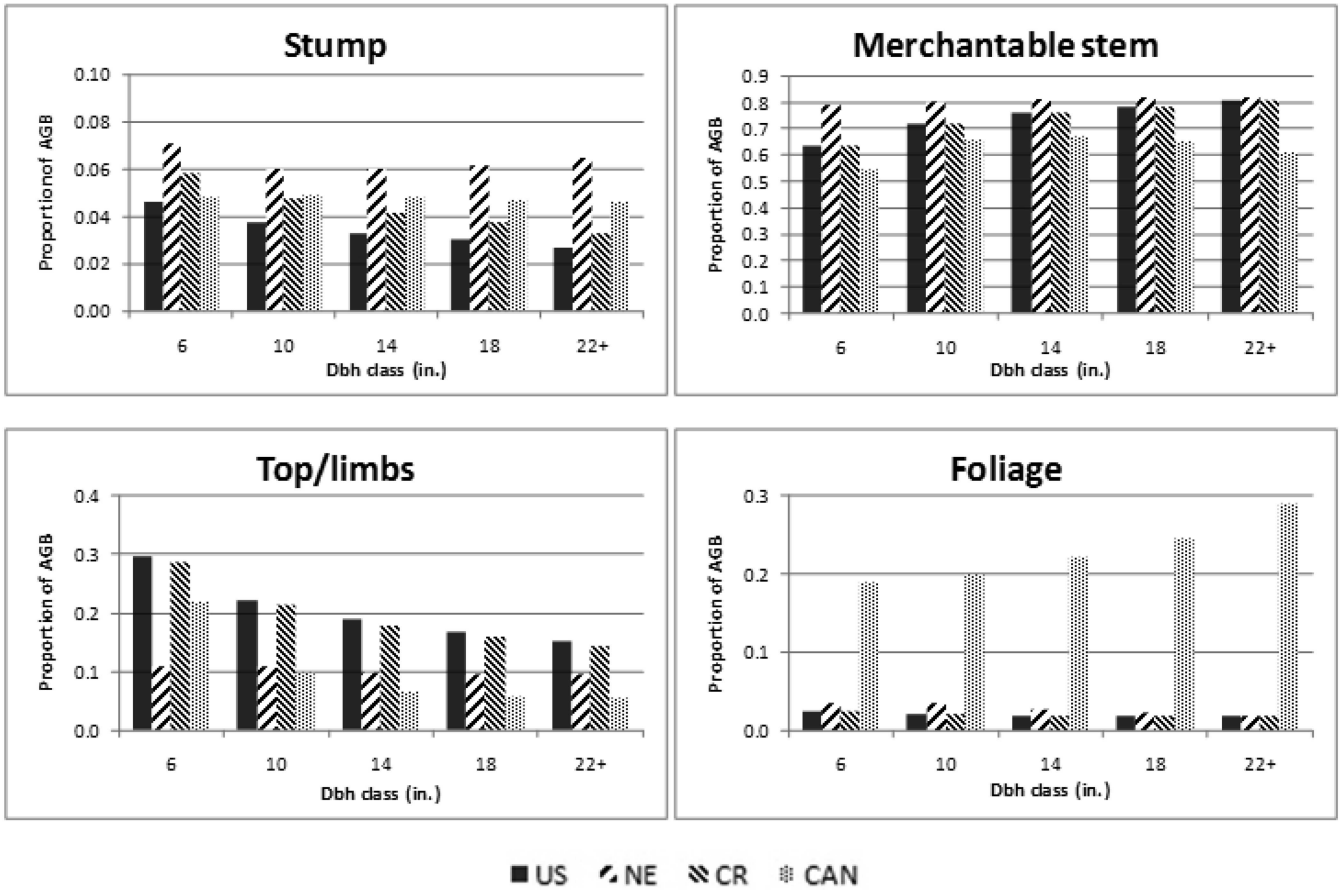

Figure 1. Component ratios of dry biomass for hardwood species by dbh class. Horizontal axis labels represent midpoint of 2-in. dbh classes. AGB, aboveground biomass; US, United States; NE, northeastern; CR, the component ratio method; CAN, Canadian.

but were much smaller (0.22–0.06). For softwood species, the US and CR methods had similar T ratios (US was slightly higher) that decreased with increasing tree size (Figure 2). The NE method was again mostly invariant to tree size (~0.12). For the smallest dbh class, the softwood T ratio produced by CAN (0.27) was nearly twice the magnitude of those found in the other methods and the T ratio for the largest dbh class (0.07) was nearly half the size of the other T ratios reported.

The US F ratio was used for the CR method and thus the same ratios are produced for both methods. For hardwood species, the NE F ratios were similar but slightly larger than the US/CR method (Figure 1). The hardwood F ratios produced by the CAN method were much larger and exhibited a trend opposing the other methods with F ratios increasing with increasing tree size. Similar results were found for softwood species, except that the ratios were larger than those for hardwoods. The relationship between US/CR (0.07–0.05) and NE (0.10–0.07) methods showed the NE F ratios were about 50% larger (Figure 2). The CAN method again exhibited increasing F ratio with increasing tree size, and the ratios were about 2 times those of US/CR.

Component Biomass

From the ratios reported above, the biomass of any component is easily determined by applying the ratio to the AGB value. Although the biomass ratios are the same for some components (e.g., US and CR F ratios), the actual biomass in each component differs among the four methods because the AGB values differ. Also note that although some components have ratios that decrease with tree size (e.g., T ratios), component biomass always increases with tree size. Figure 3 depicts the relationships between the estimates from the four methods as a percentage difference from the CAN estimates (CAN was used as the basis to facilitate graphic display).

For hardwood stump biomass, comparisons among the four methods showed that the NE method predicts the highest values (Figure 3a). The CR and US techniques have lower hardwood stump biomass predictions, with values very similar to CAN for small trees and nearly 40% smaller for large trees. Similar patterns were found for softwood stump biomass; however, the methods were in closer agreement than for hardwoods. In particular, there was better agreement between methods for the larger tree sizes, where US, NE, and CR were all within ±20% of the CAN method. The fairly wide range of stump biomass values that occurs across the four methods suggests that there may be difficulty or differences in defining the stump component (e.g., inconsistent stump heights, separation of roots from stump), which results in varying assessments of the contribution of the stump to AGB.

The net merchantable stem biomass component is perhaps the most important because it comprises a relatively large portion of AGB. As with hardwood stumps, the NE method produces the largest biomass estimates for the merchantable stem, whereas the CAN method provides the least amount of hardwood merchantable stem biomass (Figure 3b). The US and CR procedures are very similar for trees 10-in. dbh and larger. The primary difference between US and CR is for trees less than 10-in. dbh, where differences

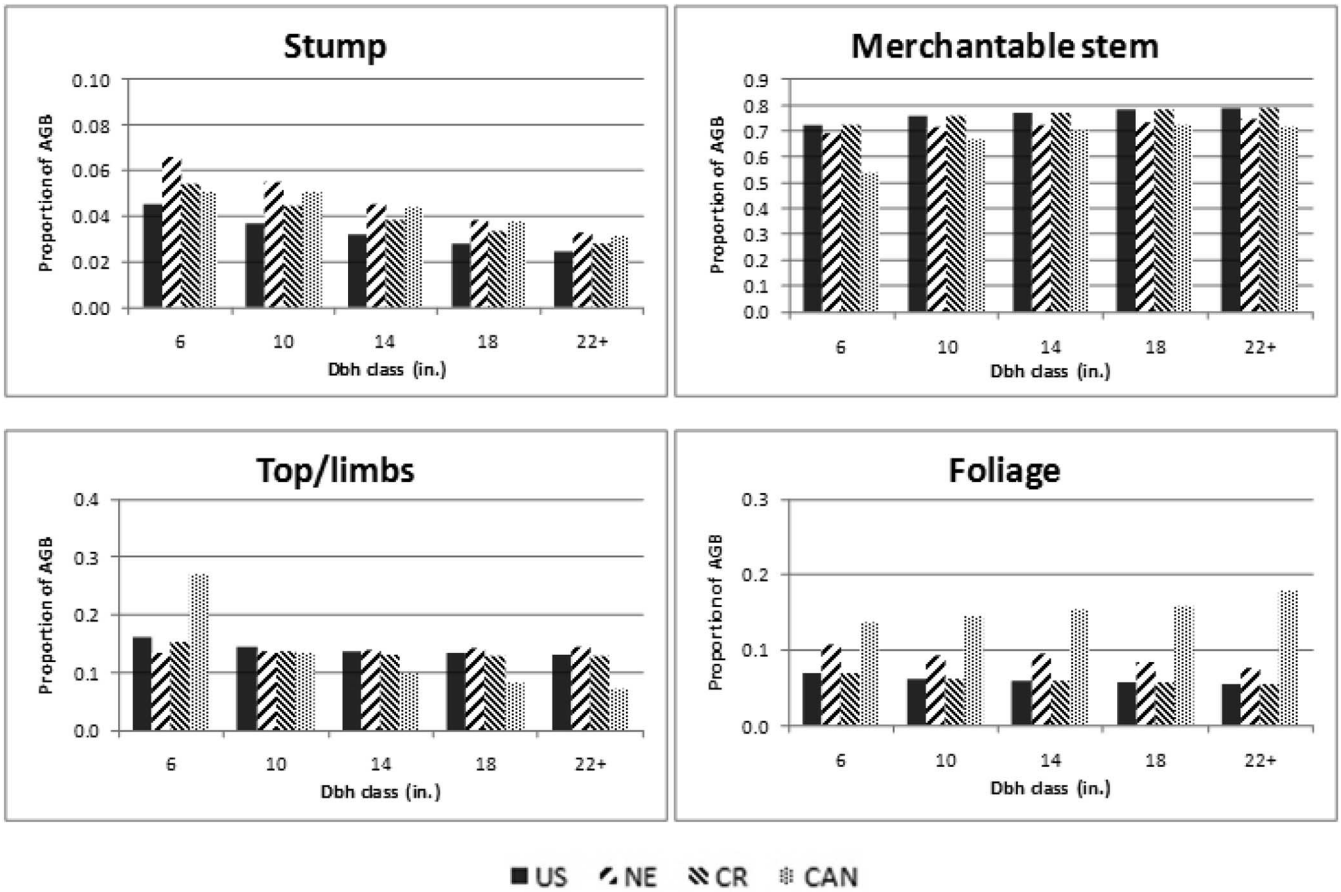

Figure 2. Component ratios of dry biomass for softwood species by dbh class. Horizontal axis labels represent midpoint of 2-in. dbh classes. AGB, aboveground biomass; US, United States; NE, northeastern; CR, the component ratio method; CAN, Canadian.

of roughly 30% are found for the smallest trees. The US method has the largest softwood merchantable stem biomass. The NE method has the next highest values, with values similar to those of US for small trees and values similar to those of CR and CAN as tree size increases. The CR estimates are only slightly higher (<3%) than those of the CAN models. The larger variability observed for hardwoods likely arises from the deliquescent branching pattern that creates difficulty in (1) determining at forks the assignment of wood to bole versus branches, and (2) consistently obtaining a merchantable bole that ends exactly at a 4-in. top diameter because of abrupt diameter changes where forks occur.

There are some relatively large differences in biomass of top/limbs for hardwoods. The CR and US methods have somewhat similar trends for estimates of biomass in top/limbs for hardwoods, but the US is the larger of the two (Figure 3c). The NE equations produce top/limbs biomass estimates that are less than those obtained from the CR and US methods. The CAN method generally yields the smallest hardwood top/limbs estimate, except for the NE method applied to trees under 8-in. dbh. The CAN approach for top/limbs biomass of softwoods is noticeably larger than the other methods for the smallest tree sizes, where differences are nearly −50%, −40%, and −25% compared with the CR, NE, and US methods, respectively. At the largest tree sizes, the CR, NE, and US methods were approximately 70%, 110%, and 120% larger, respectively, than CAN equations.

The CAN method produces the largest foliage biomass estimates for both hardwoods and softwoods (Figure 3d). The hardwood foliage estimates for the CR, US, and NE methods are only 20% or less of those obtained from CAN equations, which is at least partly because of the inclusion of twig biomass along with leaf biomass in the CAN study. There is a difference of nearly 50% between CR and NE for small hardwood trees; however, the US, NE, and CR methods have relatively small differences for biomass foliage on large hardwoods. Generally, there is better agreement among methods for softwood foliage biomass estimates. A trend similar to hardwoods is noted in that (1) agreement among the US, NE, and CR methods is poorest for smaller trees and improves as tree size increases; (2) the CR method gives values roughly 50% smaller than the NE equations for the smallest trees; and (3) the same relative ranking exists among the methods.

The results for tops/limbs and foliage indicate that (1) some differences in component definitions potentially exist, particularly for hardwood species, and/or (2) biomass is poorly estimated for these components. A primary issue here is that the CAN method includes twigs in foliage biomass, whereas the US, NE, and CR methods do not (it is assumed that twigs are included in tops/limbs component). Thus, a more valid comparison may be made by combining the T and F components for each method. These results show the proportion of AGB contained in the tops/limbs/foliage (T + F) for CAN is still high compared with the other methods; however, the discrepancies are not as large. This suggests that divergence among the methods is not attributable to definitional differences alone. It is plausible that high levels of variability for these components produce inconsistent results across studies. This may be especially true for hardwood species, where numbers/sizes of branches

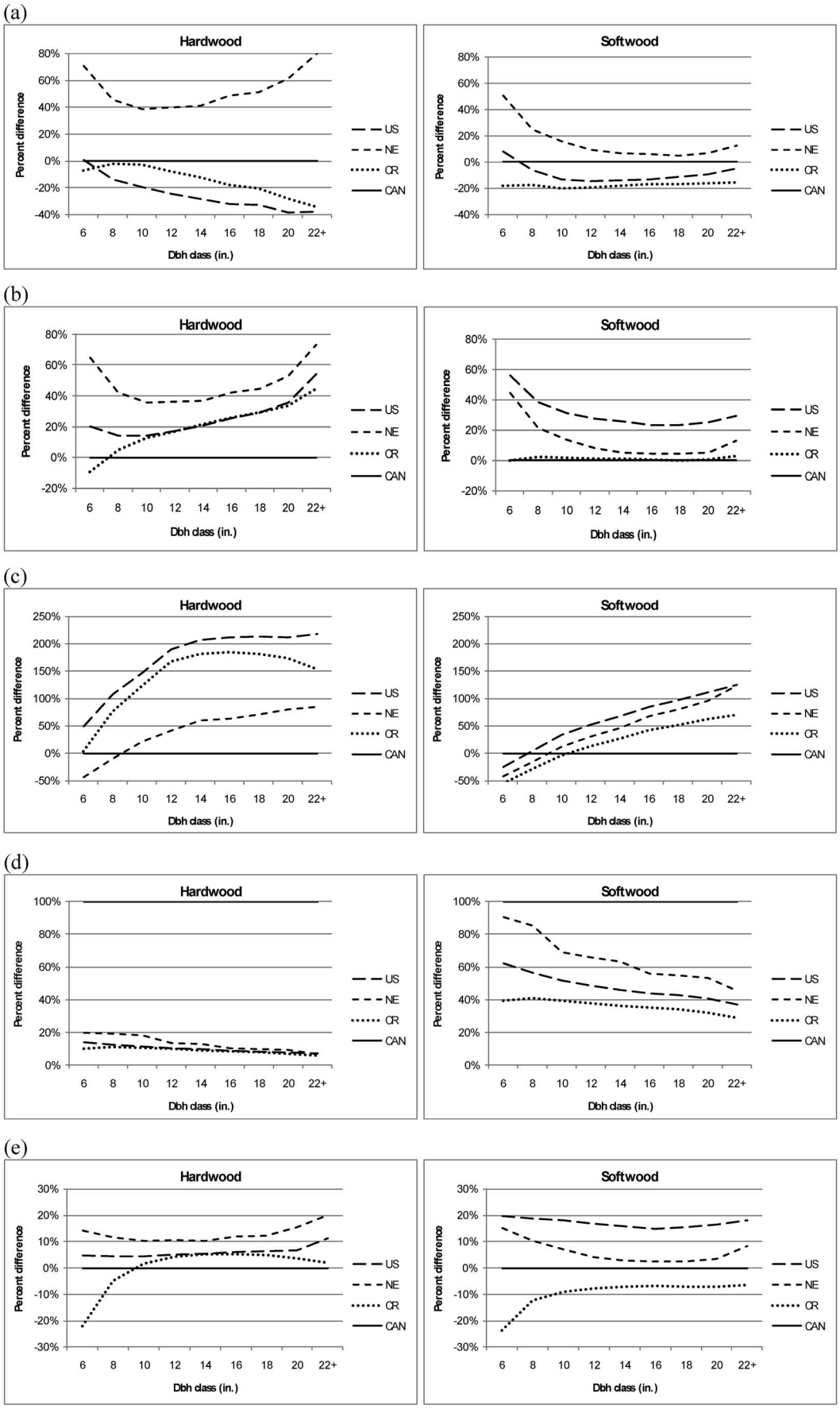

Figure 3. Percentage differences (as compared with CAN method) in dry biomass of hardwood and softwood species by dbh class for stump (a), net merchantable stem (b), top/limbs (c), foliage (d), and aboveground biomass (e). Horizontal axis labels represent midpoint of 2-in. dbh classes. US, United States; NE, northeastern; CR, the component ratio method; CAN, Canadian.

Table 2. Mean and 95% confidence bounds of dry biomass (lbs/ac) by component for hardwoods, softwoods, and all species combined.

		Hardwood			Softwood			All spp.		
Component	Method	Mean	95% CI_L	95% CI_U	Mean	95% CI_L	95% CI_U	Mean	95% CI_L	95% CI_U
Stump	US	2,147[a]	2,080	2,214	486[a,b]	452	520	2,633[a]	2,560	2,705
	NE	3,900[b]	3,744	4,056	621[c]	579	663	4,521[b]	4,362	4,680
	CR	2,499[c]	2,421	2,578	452[a]	420	484	2,952[c]	2,869	3,034
	CAN	2,641[c]	2,543	2,739	528[b]	490	565	3,168[d]	3,065	3,272
Merchantable stem	US	43,942[a]	42,441	45,442	11,470[b]	10,623	12,318	55,412[a]	53,733	57,091
	NE	52,090[b]	50,355	53,825	9,964[a,b]	9,234	10,695	62,054[b]	60,231	63,878
	CR	43,282[a]	41,797	44,766	8,968[a]	8,291	9,644	52,249[a]	50,665	53,834
	CAN	36,301[c]	35,016	37,585	8,911[a]	8,198	9,625	45,212[c]	43,778	46,646
Top/limbs	US	12,668[a]	12,275	13,060	2,115[a]	1,962	2,267	14,782[a]	14,370	15,195
	NE	6,339[b]	6,135	6,542	1,881[a]	1,743	2,019	8,219[b]	7,983	8,456
	CR	11,083[c]	10,737	11,428	1,550[b]	1,435	1,665	12,633[c]	12,278	12,987
	CAN	5,561[d]	5,379	5,743	1,613[b]	1,506	1,720	7,174[d]	6,969	7,379
Foliage	US	1,295[a]	1,253	1,337	908[a]	843	973	2,203[a]	2,128	2,279
	NE	1,737[b]	1,684	1,790	1,239[b]	1,151	1,326	2,976[b]	2,878	3,074
	CR	1,190[c]	1,151	1,228	699[c]	648	751	1,889[c]	1,827	1,951
	CAN	12,822[d]	12,351	13,293	2,014[d]	1,867	2,161	14,836[d]	14,351	15,321
Aboveground	US	60,051[a,b]	58,058	62,044	14,979[a]	13,880	16,078	75,030[a]	72,813	77,247
	NE	64,065[b]	61,945	66,186	13,705[a]	12,709	14,701	77,770[a]	75,507	80,034
	CR	58,053[a]	56,112	59,995	11,670[b]	10,795	12,544	69,723[b]	67,657	71,789
	CAN	57,324[a]	55,370	59,278	13,066[a,b]	12,078	14,054	70,390[b]	68,258	72,523

CI_L, lower boundary of confidence interval; CI_U, upper boundary of confidence interval; NE, northeastern; CAN, Canadian.
[a,b,c,d] Within-component estimates with the same superscript are not significantly different (95% confidence level).

and amounts of foliage can vary substantially depending on tree history and current growing conditions. For example, the NE and CAN methods differ substantially in T + F ratios for hardwood species, but they agree rather well for softwood species (Figures 1 and 2).

Despite the variations in component biomass across the four methods, the estimates for AGB do not differ tremendously (Figure 3e). For hardwood species, the NE equations result in the highest AGB estimates. The US method had similar trends in relation to tree size, albeit with slightly smaller estimates than NE. The CR method gave results 20% smaller than the CAN method for small trees and up to 5% higher than CAN for trees of 14-in. dbh and larger. Also, the CR and US methods provided comparable results for trees in the 12- to 18-in. dbh range. For softwood AGB estimates, the methods performed similarly to the hardwoods in relation to tree size with two primary exceptions: (1) the US method resulted in higher estimates than the NE method, and (2) the CR estimates were always less than (5–20% smaller) the CAN estimates.

Population Estimates

The magnitude of the population estimates arising from the New York data generally reflected the trends described above for each method (Table 2). It is shown here that for hardwood stump biomass, the only estimates that are statistically not different are those from the CR and CAN methods. For softwood stump biomass, the US method was not significantly different from the CR (lower) and CAN (higher) methods, although CR and CAN were significantly different from each other. Despite the nonsignificant differences in stump biomass estimates between some methods for both hardwood and softwood species groups, there were no nonsignificant differences among methods across all species. For hardwood merchantable stem biomass, the US and CR methods produce results that are not significantly different. Statistically significant differences among methods for softwood merchantable stem biomass are not as prevalent, and thus the results across all species are the same as those for hardwoods; that is, US and CR have a nonsignificant difference. All methods had significantly different top/limb biomass estimates for hardwoods and for all species combined. However, for softwood top/limb biomass, the US versus NE and CR versus CAN comparisons had nonsignificant differences. Significant differences existed between all methods for foliage biomass estimates regardless of species aggregation. For AGB in hardwood species, the CAN, CR, and US estimates were not statistically different. Of these three methods, US had the highest biomass estimate, and this estimate was not different from the NE estimate (which was the largest of all methods). For AGB in softwood species, CR and CAN had the smallest values, and these were not statistically different. There were also nonsignificant differences between the CAN, NE, and US methods. Across all species, AGB was not different for NE versus US and CAN versus CR comparisons.

Methodology Considerations

Choosing the appropriate method for a specific application requires consideration of many factors. A primary factor is whether the component definitions are consistent with desired outputs. For instance, the CAN method includes twigs in estimates of foliage biomass—if an estimate of foliage biomass excluding twigs is needed, then perhaps a different method would be more appropriate. The Methods section describes various assumptions (e.g., volume ratios derived from taper equations) that had to be made to obtain values for each component as defined in this study. Analysts should look closely at potential biomass estimators to understand how each component is defined and evaluate how any necessary additional breakdowns may be accomplished prior to selection of a specific method.

Both the NE and US methods use models to predict AGB based on tree dbh. The forms of these models result in nonlinear increases in AGB as dbh increases. Generally, this approach works well unless the models are extrapolated to larger dbh values that were not part of the model fitting data. The extrapolation usually results in overprediction for the larger trees. Jenkins et al. (2003) recognized this limitation; however, data constraints restricted the upper dbh limit to about 29 in. For the NE method, the data used by Monteith

(1979) rarely exceeded 20 in. dbh, Wiant (1977) reported a maximum size of 16 in. dbh, and Young et al. (1980) presented tables generally up to 20 in. dbh for softwoods and 26 in. dbh for hardwoods (although the actual diameter ranges within the data were not provided). The range of dbh found in the CAN study varied widely among species, with the upper limit at about 29 in. (white oak). Unlike the US and NE methods, CAN predictions are also subject to the influence of tree height – this may ameliorate somewhat the overprediction for large trees. In contrast, the CR method essentially derives AGB from expansion of the bole biomass as determined from bole volume. Thus, the concern regarding large size trees is diminished. Given the maximum tree diameters listed in Table 1 and the results in Table 2 showing that the US and NE methods result in higher predicted amounts of biomass, the performance of the methods for AGB of larger trees was evaluated. For trees less than 25 in. dbh, the CR and CAN methods were essentially the same, with US and NE being 10 and 13% larger, respectively. For trees having dbh of 25.0-in. and larger, CR and CAN were again nearly identical; however, the US method was 15% larger and the NE method was 22% larger. Although determination of which techniques are the most accurate is without resolution, it appears that the US and NE methods are effected to a greater extent by large trees than the CR and CAN methods. Also, the discrepancy between US and NE increases when larger sized trees are considered.

Among the four methods, both implicit and explicit approaches are used to develop biomass component ratios. The ratios for CAN are essentially a byproduct of the relationships between model predictions for the different components and their sum (AGB). A slightly different approach was used for the NE method, where weights of tops/limbs and leaves are subtracted from AGB (less stump) to obtain merchantable bole weight. For this study, the biomass for the stump was added and ratios then computed accordingly. Both the CAN and NE methods are component weight based; that is, AGB is simply the sum of the components, and the ratios arise from the component proportions. The ratios for the US method are predicted from models. Application of these ratios to model-predicted AGB results in biomass weights for individual components. For the CR method, the US ratios are used. However, it is actually the relationships between the ratios that drive the component biomass; that is, component biomass is scaled via ratios to the merchantable bole biomass derived from volume and wood density values. The US and CR methods primarily rely on the ratios to determine the component biomass weights. It should also be noted that the NE and US techniques are constrained to a predicted AGB value, whereas the CR and CAN methods rely on sums of components to obtain AGB.

Although the effects on estimates of biomass and associated components are not clear, readers should also be aware of differences among methods in species aggregations. For the species used in this study, the CR method has 5 species-specific equations (balsam fir, eastern hemlock, sugar maple, American beech, black cherry), with the remainder being grouped with other similar species. All models used for the NE method were species-specific except for paper birch. Similarly, all models were specific to the species for the CAN method. The US method differs notably from the others in that no species-specific models are available. There are 4 species groups for hardwoods and 5 species groups for softwoods. The broad groupings found in the US method should work reasonably well when applied at the regional level according to Jenkins et al. (2003); however, depending on how the region is delineated and the influence of studies from within that region on the overall analyses, predictive performance may be erratic for a given species or set of species.

Another factor to be considered when selecting a biomass estimation method is the set of population characteristics. If, for example, the population consists primarily of softwood species, then the results for softwoods should be given more emphasis than outcomes from all species combined. Also, if only a few (or one) species are of interest in an area where local volume equations are available, they can be used in conjunction with the CR method to help calibrate predictions to local conditions.

These results may motivate some foresters to change biomass estimation methods. Although this is recommended if demonstrably more accurate biomass estimates would be obtained, foresters must be also aware of the implications on users of the data. Until recently, FIA biomass in the northeastern United States was computed from the NE equations. When the CR method was implemented, all tree biomass values were recalculated. This change in methodology resulted in, for example, an 18% decrease in balsam fir AGB in Maine. This can be problematic to forest resource managers, whose management strategies were based on the larger estimates from NE equations. Because of the lack of empirical data, it is unknown which method provides the most accurate estimates. However, if the new method more accurately reflects the actual state of the biomass resource, the resource will ultimately be better managed than it would with the previous estimates. Such changes also require recalculation of older data to obtain accurate estimates of trends in biomass over time.

Conclusion

The results of this study affirmed the existence of widely varying estimates among the four methods for tree component biomass. In comparison, estimates of AGB were relatively consistent. In addition, the differences in how tree components were defined (or lacked definition) were brought to light for each study. Forest managers should study closely the underlying assumptions, biomass component breakouts, and prediction techniques of each method before adoption. When applied to a broad population, the CAN and CR methods provide quite similar results for AGB. The US method resulted in higher estimates than those of CAN and CR, whereas the NE method produced the highest AGB estimates. The sources of variation among methods may include (1) differing protocols/definitions in the data collection phase, (2) promulgation of methods that lack rigorous validation, (3) development of hybrid methods, and/or (4) application of equations designed for broad geographic areas that may not be accurate in the northeastern United States.

Further study of biomass is needed in the northeastern United States. A regionwide biomass study with consistent definitions and measurement protocols throughout would be paramount in establishing reliable biomass estimators. This would preclude the need to adopt methods that were developed for much broader geographic scope (US and CAN) or rely on a mix of numerous small studies performed in various parts of the region (NE). It should be noted that the CR method is adapted to the northeastern United States via the volume equations developed by Scott (1981). However, the ratios that distribute the biomass to each component are from the US method, which may or may not accurately represent the ratios found in the northeastern United States. Proper management of

forests from a biomass perspective requires reliable tree-level estimates such that the actual state of the resource is accurately represented.

Literature Cited

Benjamin, J.G., R.J. Lilieholm, and C.E. Coup. 2010. Forest biomass harvesting in the Northeast: A special-needs operation? *North. J. Appl. For.* 27:45–49.

Clark, A. III, D. Phillips, and D. Frederick. 1985. *Weight, volume, and physical properties of major hardwood species in the Gulf and Atlantic Coastal Plains.* US For. Serv. Res. Pap. SE-250. 72 p.

Cost, N.D., and J.P. McClure. 1982. *Multi-resource inventories: Techniques for estimating biomass on a statewide basis.* US For. Serv. Res. Pap. SE-228. 35 p.

Froese, R.E., D.R. Shonnard, C.A. Miller, K.P. Koers, and D.M. Johnson. 2010. An evaluation of greenhouse gas mitigation options for coal-fired power plants in the US Great Lakes States. *Biomass Bioenerg.* 34:251–262.

Galik, C.S., R. Abt, and Y. Wu. 2009. Forest biomass supply in the Southeastern United States: Implications for industrial roundwood and bioenergy production. *J. For.* 107:69–77.

Hahn, J.T. 1984. *Tree volume and biomass equations for the Lake States.* US For. Serv. Res. Pap. NC-250. 10 p.

Heath, L.S., M.H. Hansen, J.E. Smith, P.D. Miles, and B.W. Smith. 2009. Investigation into calculating tree biomass and carbon in the FIADB using a biomass expansion factor approach. Number 24 in *Forest Inventory and Analysis (FIA) Symposium 2008*, McWilliams, W., G. Moisen, and R. Czaplewski, R. (comps.). Proc. RMRS-P-56CD. US For. Ser., Rocky Mountain Research Station, Fort Collins, CO.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey. 2003. National scale biomass estimators for United States tree species. *For. Sci.* 49(1):12–35.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey. 2004. *Comprehensive database of diameter-based biomass regressions for North American tree species.* US For. Serv. Gen. Tech. Rep. NE-319. 45 p. [1 CD-ROM].

Lambert, M.-C., C.-H. Ung, and F. Raulier. 2005. Canadian national tree aboveground biomass equations. *Can. J. For. Res.* 35:1996–2018.

Lindsay, J.J., A.H. Gilbert, and T.W. Birch. 1992. *Factors affecting the availability of wood energy from nonindustrial private forest lands in the Northeast*. US For. Serv. Res. Bull. NE-122. 19 p.

Monteith, D.B. 1979. *Whole tree weight tables for New York.* SUNY College of Env. Sci. and For. AFRI Res. Rep. No. 40. 64 p.

Raile, G.K. 1982. *Estimating stump volume.* US For. Serv. Res. Pap. NC-224. 4 p.

Reams, G.A., Smith, W.D., Hansen, M.H., Bechtold, W.A., Roesch, F.A., and Moisen, G.G. 2005. The Forest Inventory and Analysis sampling frame. P. 11–26 in *The enhanced forest inventory and analysis program: National sampling design and estimation procedures,* Bechtold, W.A., and P.L. Patterson (eds.). US For. Serv. Gen. Tech. Rep. SRS-80.

Scott, C.T. 1981. *Northeastern forest survey revised cubic-foot volume models.* US For. Serv. Res. Note NE-304. 3 p.

Smith, W.B., and G.J. Brand. 1983. *Allometric biomass equations for 98 species of herbs, shrubs, and small trees.* US For. Serv. Res. Note NC-299. 8 p.

Smith, W.B. 1985. *Factors and equations to estimate forest biomass in the North Central region.* US For. Serv. Res. Pap. NC-268. 6 p.

Ter-Mikaelian, M., and M. Korzukhin. 1997. Biomass equations for sixty-five North American tree species. *For. Ecol. Manage.* 97:1–24.

Tritton, L.M., and J.W. Hornbeck. 1982. *Biomass equations for major tree species of the northeast.* US For. Serv. Gen. Tech. Rep. NE-69. 46 p.

Van Deusen, P.C. 2004. Forest inventory estimation with mapped plots. *Can. J. For. Res.* 34:493–497.

Wartluft, J.L. 1977. *Weights of small Appalachian hardwood trees and components.* US For. Serv. Res. Pap. NE-366. 4 p.

Westfall, J.A., and C.T. Scott. 2010. Taper models for commercial tree species in the Northeastern U.S. *For. Sci.* 56:515–528.

Wharton, E.H., T.S. Frieswyk, and A.M. Malley. 1985. *Aboveground tree biomass statistics for Maine: 1982.* US For. Serv. Resour. Bull. NE-86. 116 p.

Wharton, E.H., and D.M. Griffith. 1998. *Estimating total forest biomass in Maine, 1995.* US For. Serv. Resour. Bull. NE-142. 50 p.

Wiant, H.V. Jr., G.E. Sheetz, A. Golaninno, J.C. DeMoss, and F. Castaneda. 1977. *Tables and procedures for estimating weights of some Appalachian hardwoods.* West Virginia University Agricultural and Forestry Experiment Station Bull. 659T. 36 p.

Young, H.E., J.H. Ribe, and K. Wainwright. 1980. *Weight tables for tree and shrub species in Maine*. Univ. of Maine Life Sci. and Agric. Exp. Stn. Misc. Rep. 230. 84 p.