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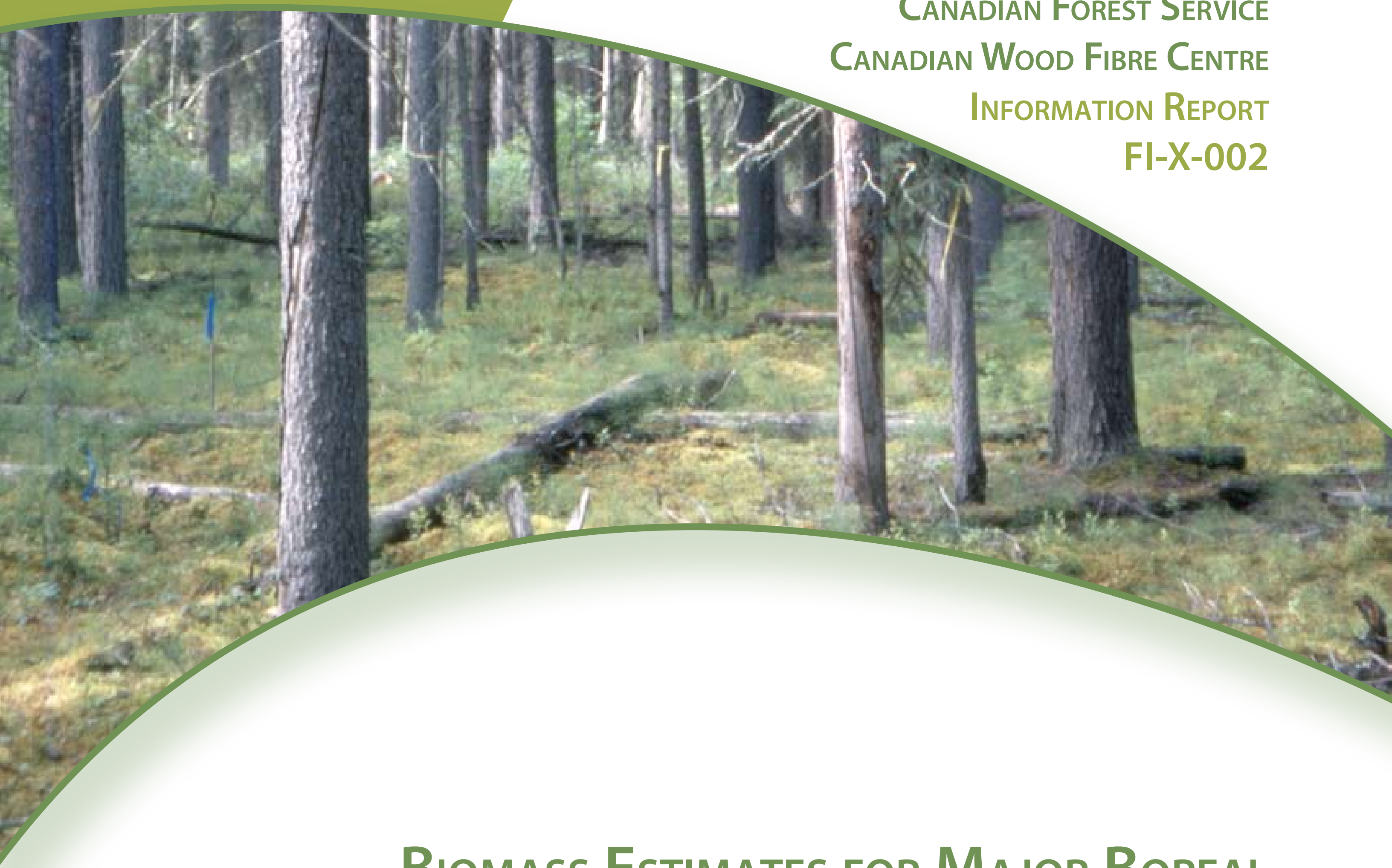

Biomass Estimates for Major Boreal Forest Species in West-Central Canada

Z. Miao and C. Li

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ABSTRACT

Forest biomass is the second-largest renewable energy resource in Canada, representing a major pool in the global carbon budget, but better estimates of forest biomass are needed. In the 1980s, numerous empirical biomass equations were developed for estimating forest biomass. However, many of these were reported inconsistently by different authors in terms of their form and parameter values, even for the same species, which has complicated their application. This study was undertaken to review existing methods of biomass measurement and estimation, and to identify and evaluate the existing biomass equations that might be most suitable for estimating the biomass of major species at a large spatial scale in west-central Canada. Seventeen commonly used biomass equations and two biomass extrapolation methods were compared at the individual tree and stand scales for major species in west-central Canada. The biomass equations usually provided more consistent estimates for medium-sized trees than for small or large trees. Equations developed for the Prairie provinces and/or for national data sets were more appropriate for estimating the individual tree biomass of six boreal forest species in west-central Canada. There were no significant differences between the mean tree method and the normal distribution approach for extrapolating from individual tree biomass to stand biomass. For shrub understory biomass, there were no significant differences among the species-specific equations. For estimating belowground biomass, equations based on the aboveground biomass are recommended; therefore, accurate estimation of aboveground biomass is a prerequisite for accurately determining belowground biomass.

RESUME

La biomasse forestière est la deuxième source d'énergie renouvelable en importance au Canada et un important réservoir dans le bilan mondial du carbone. Elle doit toutefois faire l'objet d'estimations plus précises. De nombreuses équations empiriques ont été élaborées durant les années 1980 afin d'estimer la biomasse forestière. Cependant, divers auteurs n'ont pas systématiquement fait état de la forme et des valeurs des paramètres de nombre de ces équations, même celles portant sur une même espèce, ce qui a eu pour effet de compliquer l'application de celles-ci. La présente étude a été entreprise afin d'examiner les méthodes existantes de mesure et d'estimation de la biomasse et de déterminer et d'évaluer celles qui pourraient être les plus utiles pour estimer la biomasse des principales espèces du centre-ouest du Canada à une grande échelle spatiale. Nous avons comparé 17 équations de la biomasse et deux méthodes d'extrapolation de la biomasse couramment utilisées au niveau des arbres et des peuplements individuels pour les principales essences du centre-ouest du Canada. Les équations de la biomasse fournissaient habituellement des estimations plus constantes à l'égard des arbres de dimensions moyennes qu'à l'égard des arbres de petites ou de grandes dimensions. Les équations élaborées pour les provinces des Prairies et/ou pour des ensembles de données nationaux convenaient mieux à l'estimation de la biomasse des arbres individuels de six essences de la forêt boréale du centre-ouest du Canada. Nous n'avons constaté aucune différence significative entre la méthode fondée sur l'arbre moyen et la méthode faisant appel à la distribution normale pour extrapoler la biomasse d'un peuplement à partir de la biomasse des arbres individuels. Dans le cas de la biomasse des arbustes du sous-étage, nous n'avons relevé aucune différence significative entre les équations propres à une espèce. Comme il est recommandé d'utiliser des équations fondées sur la biomasse aérienne pour estimer la biomasse souterraine, il est donc essentiel d'estimer avec précision la biomasse aérienne afin d'être en mesure de déterminer avec exactitude la biomasse souterraine..

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Forest biomass is the second-largest renewable energy resource in Canada and a major pool in the global carbon (C) budget. Almost 50% of Canada's land base is covered by forest, and the country's forest represents as much 10% of the world's forest (Penner et al. 1997). In 1993, for example, Canada had over 2.60×10^{10} t of oven-dry forest biomass, with an average of 90.87 Mg ha^{-1}, which is equivalent to the energy produced by 8.20×10^{7} barrels of oil, Canada's oil requirements for 151 years (at 1993 rates of consumption) (Penner et al. 1997). The boreal forest is the prime producer of forest biomass, because of its wide extent (approximately 2.17×10^{8} ha across the country, which amounts to about 52% of Canada's total forest area) (Kurz and Apps 1993, 1999; Penner et al. 1997; Apps et al. 1999). In west-central Canada (i.e., the Prairie provinces [Alberta, Saskatchewan, and Manitoba] and the Northwest Territories), the boreal forest is dominated by softwood and mixedwood stands with species such as white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) BSP), jack pine (*Pinus banksiana* Lamb.), lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.), balsam fir (*Abies balsamea* (L.) Mill.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), and white birch (*Betula papyrifera* Marsh.) (Singh 1982; Wilkinson 1990; Lowe et al. 1996; Tannas 1997).

A better understanding of forest biomass forecasting is needed because of the growing use of biomass inventory data and the contribution of Canada's forests to renewable energy resources and carbon stores (Penner et al. 1997; Schroeder et al. 1997; Apps et al. 1999; Jenkins et al. 2003). During the past few decades, particularly in the 1980s and early 1990s, tremendous efforts have been devoted to quantifying this biomass resource and its dynamics (Kurz et al. 1992; Kurz et al. 1996; Kurz and Apps 1999; Parresol 2001; Banfield et al. 2002; Elliott et al. 2002; Lee et al. 2002). As an essential tool for forest biomass estimation, biomass equations for individual trees have been produced in studies of forest production and its correlation with stand density, in studies comparing biomass and production for individual tree species, in studies of forest fuel and root estimates, and in studies mapping and classifying regional forest carbon budgets (Schroeder et al. 1997; Ter-Mikaelian and Korzukhin 1997; Jenkins et al. 2003). In the forestry literature, however, different biomass estimation equations may be reported for the same species, because such equations have often been published inconsistently, in terms of either the form of the equation or the parameter values for a given species at the same sampling site (Schroeder et al. 1997; Ter-Mikaelian and Korzukhin 1997; Jenkins et al. 2003). Biomass equations are mainly dependent on factors such as study purpose and field conditions at the sampling sites (Ter-Mikaelian and Korzukhin 1997; Jenkins et al. 2003); diversity of forest vegetation types and complexity of forest ecosystem structure; and differences in biomass component definitions, sampling methods, sample sizes, measurement precision, regression-fitting methods, and/or equation forms (Banfield et al. 2002; Jenkins et al. 2003).

Although existing predictive equations offer an alternative to destructive sampling of trees in the development of local equations, the variability of biomass equations usually complicates their application at different sites for a given species, and different conclusions may be drawn when different equations are used. BIOPAK software version 2.5 (Forest Resources Systems Institute, P.O. Box 1785, Clemson, SC, USA 29633–1785; http://www.forsonline.org), for example, included more than 70 biomass equations in its library, but users were warned to carefully select equations and to thoroughly examine any results obtained according to study purpose, site condition, and field sample data (Means et al. 1996). Unless a particular biomass equation was developed exclusively for the species and study region of interest, or under conditions typical of the study site, an equation for one site cannot be directly applied to another site. Users may also wonder which equation is most appropriate for their particular species and study site, and what application limits might exist. Unfortunately, little information is available in the literature about how particular biomass equations were developed and the likely magnitude of error or bias if they are applied to other sites (Alaback 1986; Schroeder et al. 1997). Some previous reviews of biomass equations either need to be updated or were designed to suit local geographic needs (Penner et al. 1997; Schroeder et al. 1997; Jenkins et al. 2003). Therefore, there is a current need to better understand application limits and the potential error associated with using biomass equations across different study sites.

Information on scaling up site-specific biomass equations to larger areas is critical for estimating regional or global spatial distribution of biomass. Biomass equations are often combined with remote sensing data and forest inventory databases to map and classify spatially explicit aboveground biomass (Jenkins et al. 2003). However, because most published biomass equations were developed using trees sampled from isolated study sites or from very small regions, users should be cautious about using existing biomass equations with forest inventory data sets at large spatial scales. For instance, when biomass equations are used at large spatial scales, regional parameter values are often required, and the bias and error of site-specific biomass equations may be amplified (Ter-Mikaelian and Korzukhin 1997; Jenkins et al. 2003). Currently, various biomass equations can be easily collected for a given species at a given site, but calibration of these functions is limited to a specific area, since representative high-quality biomass sample data sets are lacking for large-scale forests. Calibration (or validation) of biomass equations with a local sample data set is applicable only for the specific sampling site and cannot be extended to larger scales. To calibrate existing biomass equations or develop new biomass equations that are consistent for a large area such as the west-central boreal forest of Canada, it would be necessary to sample hundreds, if not thousands, of trees of different sizes from a representative sample of species and sites across the region. This would be very expensive and has been regarded as a major barrier to the application of existing biomass equations at large scales (Means et al. 1996; Ter-Mikaelian and Korzukhin 1997).

The objective of this study was to review existing methods of biomass measurement and estimation, and to identify and evaluate the existing biomass equations that might be most suitable for estimating the biomass of major species at a large spatial scale in west-central Canada (i.e., the Prairie provinces [Alberta, Saskatchewan, and Manitoba] and the Northwest Territories). This report begins with a review of methods of biomass sampling and forecasting. A total of 17 biomass equations that have been commonly used to estimate overstory, understory, and belowground biomass dynamics in Canada or the northern United States (north of about 40° N) were identified through an extensive literature review. Existing publications on the dynamics of boreal forest biomass in west-central Canada were used to create a test data set to evaluate the biomass equations at the level of individual trees and stands. The identification and evaluation of the 17 equations were carried out from the standpoints of individual tree biomass, stand biomass, and shrub understory biomass, and belowground biomass. For definitions of terms used in this report, refer to the Glossary in the Appendix; for a discussion of major boreal forest species in west-central Canada refer to Little (1979) and Farrar (1995).

Forest biomass dynamics are estimated through direct and indirect measurements (Kurz et al. 1992; Araújo et al. 1999; Fang et al. 2001; Corona et al. 2002; Peng et al. 2002). Direct measurement is a labor intensive, expensive, and destructive approach, consisting of cutting and weighing aboveground material in a selected area. For this method, the choice of sampling area is important, because simple extrapolation may be biased and lead to inaccurate results. In general, the chosen area is assumed to be homogeneous, but often it contains both large and small trees (i.e., spatial variability), which results in overestimation or underestimation of biomass (Araújo et al. 1999). In contrast, indirect measurement saves time and money because it uses mathematical biomass equations or combines such equations with other types of data, such as field surveys using global positioning systems, remote sensing imagery, or spatially explicit databases based on geographic information systems.

Direct Measurements

Direct measurement of stand biomass usually consists of on-site field sampling of the overstory (stem, leaves, branches, etc.), understory (shrubs, tree seedlings, grass, etc.), belowground matter, litterfall, and dead material in temporary or permanent sampling plots, and treatment of the samples in the laboratory.

Overstory Biomass

The fieldwork for overstory biomass measurement usually includes selecting trees, taking standing measurements, felling the trees, collecting dimensional data, cutting and separating the tree components, and weighing fresh components of each biomass category on site (e.g., dead and live twigs, branches, foliage, stems). Sometimes, branches are further categorized as foliage, branches ≤0.5 cm, branches 0.5–2 cm diameter outside bark (DOB), and branches >2 cm DOB. Overstory measurement also entails subsampling (e.g., of tree disks and individual components), sealing the samples securely with masking tape and plastic tape, ovendrying the samples, weighing the oven-dry samples, and taking wood density measurements of trees selected over a range of diameter classes (e.g., ≤10 cm, 11–20 cm, 21–30 cm, and >30 cm) (Alemdag 1980, 1982; Singh 1982, 1984a; Alberta Forest Service 1985a, 1985b, 1988). For instance, for stands growing on small areas (e.g., <0.1 ha), all trees are usually registered, and DOB at breast height and stump level (0.1 or 0.3 m) above ground is measured with a tape. For stands growing on larger areas (>0.1 ha), 10–20 circular subsample plots, with the largest trees at the center, are typically established, and the number of trees and the diameter at breast height (DBH; usually DOB but sometimes diameter inside bark [DIB]) are registered for each plot. After the sample trees have been felled, their height (m) and diameter at breast height and 0.3 m above ground (cm) are measured. Then, tree height is determined by means of a clinometer (with a percent scale) and a metric surveyor's tape. Tree age is recorded by counting annual rings on the disks from breast height, and total age is estimated by counting annual rings on the disks taken from the bottom of the stump (0.1 or 0.3 m height) (Singh 1982, 1984a; Johansson 1999).

For sample preparation and treatment in the laboratory, tree disk subsamples (except for dead branch subsamples) are debarked. All of the bark, wood, branches, twigs, and leaves (or needles) are ovendried for 48 h at 103 ± 2°C or until constant mass is reached. When dry, the needles or leaves are separated from the wood and foliage. Fresh mass and oven-dry biomass are usually measured to the nearest 0.1 g (Singh 1982, 1984a).

Understory Biomass

The most common technique for understory biomass measurement is collection by destructive sampling (e.g., clipping) and measurement of the aboveground vegetation. For different vegetative species, the size of sample plots differs, and each sample plot is usually divided into subplots for sampling vegetation of different sizes (Yarie and Mead 1988; Coble et al. 2001; Tremblay and Larocque 2001). Each species in a sample plot is bagged and labeled separately; hence, a given sample represents all individuals of one species collected from the same plot on the same day. For instance, Tremblay and Larocque (2001) reported that all woody species measuring 0.5–1.3 m high were harvested within a 4-m^2 plot, and one subplot of 1 m^2, always located in the southeast corner of the 4-m^2 plot, was designated for harvest of woody species less than 0.5 m tall and herbaceous species. Similarly, one subplot of 0.25 m^2, also situated in the southeast corner of the 4-m^2 plot, was designated for harvest of small herbaceous species, mosses, liverworts, lichens, and so forth. In vertical profile, the forest understory is usually classified into the following layers: ground level (about 0–2.5 cm in height), for mosses, lichens, liverworts and other small plants; grass layer, for forbs, sedges, ferns, grasses, and grasslike species (about 2.5 cm to 0.5 m); low shrub layer, for forbs and low woody shrub species 0.5–2 m in height; and sapling layer, for tall shrubs, tree seedlings, and saplings (≤3 years old) typically ≥2 m in height but below the forest canopy (Saskatchewan Tourism and Renewable Resources 1980; Yarie and Mead 1988; Quinby 1997; Thysell and Carey 2000; Coble et al. 2001; Tremblay and Larocque 2001).

The understory samples are typically placed in paper or plastic bags and returned to the laboratory for ovendrying at 65°C; dried foliage and twigs are measured separately. Leaves (or needles) of woody species are usually detached from twigs upon arrival in the laboratory, before drying.

Belowground Biomass

Belowground biomass sampling often involves excavation by hand or bulldozer and careful tracking to a root diameter of less than 2 or 5 mm. Relative horizontal positions of root systems should be mapped first, if necessary. The diameter of several randomly selected, medium-sized lateral roots (e.g., three to nine per tree) is usually measured at intervals of 20–30 cm from each tree stump to a point where the root tapers to 2 or 5 mm in diameter. Fresh weights of coarse roots (≥2 mm or ≥5 mm in diameter) are measured, and dry weights are determined on the basis of dry to fresh weight ratios obtained for subsamples. Fine roots (<2 mm or <5 mm in diameter) are usually sampled within the upper soil layer of the 10 x 15-m small plot (to a depth of 20 cm) with a cylindrical sample corer (4.7 cm inside diameter). Fine roots can be sorted into living and dead material on the basis of visible and mechanical criteria or may be grouped into three diameter classes (<1, 1–3, and 3–5 mm). In the laboratory, root biomass is weighed to the nearest 0.1 g after ovendrying at 85°C (Kajimoto et al. 1999; de Viñas and Ayanz 2000).

Litterfall Biomass

Litterfall biomass is often collected at the end of the growing season in a certain area, with traps usually located in a random manner within about 10–20 cm of the soil collar. Litterfall samples are bagged, transported to the laboratory, and ovendried for 48 h at 70°C, then weighed to the nearest 0.1 g (Coble et al. 2001).

Indirect Measurements

Methods of estimating forest biomass usually include empirical (or semi-empirical) yield tables, process-based mechanistic models, and hybrid (mixed) simulation models with or without consideration of climate change, time series, spatially implicit and explicit scales, and other factors (Alberta Forest Service 1985a, 1988; Kurz et al. 1992; Voit and Sands 1996; Lindner et al. 1997). This report focuses on empirical biomass equations.

Overstory Biomass Equations

Empirical biomass equations have usually been derived from specific sample data and represent the best description of the relation between observed data and determinant variables such as DBH (cm), tree height (m), stand age, density, volume, and basal area, determined according to a specified mathematical function (e.g., linear or nonlinear regression). If the sample data are of sufficient quantity and quality, this kind of biomass equation can be easily constructed, because contemporary statistical and computer tools allow identification of empirical curves to fit sample data and determinant variables. Of these empirical equations, two types have been widely used for estimating forest overstory biomass: dimensional analysis and the conversion of volume to biomass.

Dimensional analysis is the method most often used by foresters and ecologists to estimate individual tree biomass (Jenkins et al. 2003). This method relies on the consistency of an allometric relation between plant dimension (usually DBH or height) and biomass for a given species (or group of species) or growth form. In the biological sciences, the study of size-correlated variations in organic form and process is traditionally called "allometry" (from the Greek *allos* for "other" and *metron* for "measure") (Jenkins et al. 2003). For dimensional analysis, a researcher samples many stems spanning the diameter and/or height range of interest, and then uses a regression equation to predict the allometric relation with one or more tree dimensions (as independent variables) (Jenkins et al. 2003; Zianis and Mencuccini 2003). Table 1 lists the allometric biomass equations for whole trees and tree components most frequently used in Canada and the northern United States.

Table 1. Commonly used biomass equations for Canada and the northern United States

Formula[a]	Description and comments	References
$B = a + bD$	Linear	Aldred and Alemdag 1988
$B = a + bD^2$	Parabolic	Singh 1982, 1984a
$B = a + bD + cD^2$	Parabolic	Singh 1982, 1984a
$B = bD + cD^2$	Parabolic through origin	Aldred and Alemdag 1988
$B = a + bD + cD^2 + dD^3$	Polynomial	Singh 1982, 1984a
$B = aD^b$ or $\ln(B) = a + b\ln(D)$	Exponential or logarithmic through origin	Ter-Mikaelian and Korzukhin 1997; Lambert et al. 2005
$\ln(B) = a + b\ln(D^2)$	Logarithmic	Aldred and Alemdag 1988
$B = a + bD^2H$ or $B = bD^2H$	Combined allometric variables or combined allometric variables through origin	Alemdag and Horton 1981; Singh 1982, 1984a; Alemdag 1982, 1984; Bonnor 1985; Monserud et al. 2006
$\ln(B) = a + b\ln(D^2H)$	Logarithmic and combined allometric variables	Ouellet 1983
$\ln(B) = a + b\ln(D) + c\ln(H)$	Logarithmic	Evert 1983, 1985
$B = aD^bH^c + b(D^bH^c)^2$	Exponential and combined allometric variables through origin	Evert 1985; Lambert et al. 2005
$B = aD^2H + bDH$ or $B = aD^2H + bDH + cD^2$	Exponential and combined allometric variables through origin	Evert 1983, 1985
$B = a + bD + cH + dD^2H + eD^2 + fD^3$	Polynomial and combined allometric variables through origin	Singh 1982, 1984a
$B = \mathrm{Exp}(a + b\ln(D))$	Exponential	Jenkins et al. 2003
$B = aH\mathrm{Exp}(\mathrm{BD}^b)$	Exponential	Lee et al. 2002
$B = aX^b$	Exponential through origin	Kort and Turnock 2000
$B = aV^c$	Exponential through origin	Singh 1984b
$B = A \times \mathrm{BEF} \times V$	Linear through origin	Brown et al. 1997, 1999; Penner et al. 1997

[a] B = oven-dry biomass of the whole tree, tree components, or stand (kg/tree or Mg ha^{-1}); D = diameter at breast height, including diameter outside bark and diameter inside bark (cm); H = tree height (m); BD = basal diameter (cm/stem); X = tree age (years) at breast height; V = single tree or stand volume (m^3/stem or m^3 ha^{-1}); A = forest area (ha); BEF = biomass expansion factor; a, b, c, d, e, and f = regression coefficients.

The conversion of volume to biomass is another frequently used empirical method for estimating forest biomass, since information on forest volume is widely collected and available throughout the world. In this method, biomass expansion factors (BEFs), defined as the ratio of all stand biomass to growing stock volume, are often adopted for converting inventoried volume to biomass. In Canada's Forest Inventory 1991 (CanFI'91), for example, BEF was designed to maximize the use of existing volume inventory data and national and provincial biomass equations (Gray and Power 1997; Penner et al. 1997). A limitation of this method is that volume inventories usually do not characterize the biomass of all forest components; instead, they emphasize the commercially valuable wood. Thus, in most areas, it is necessary to develop an additional BEF to account for noncommercial components such as branches, twigs, bark, stumps, foliage, seedlings, and saplings. Furthermore, BEF is highly dependent on species, size, and site (Brown et al. 1999). For example, in CanFI'91, the BEF for converting stand pulpwood volume to stand stemwood biomass was the ratio of the sum of stemwood biomass of individual trees divided by the sum of pulpwood volumes of individual trees for each of the hypothetical stands:

$$\mathrm{BEF}_{\mathrm{pulpwood}} = \frac{\Sigma\ (\text{stemwood biomass of single trees in hypothetical stand})}{\Sigma\ (\text{pulpwood volume of single trees in hypothetical stand})} \qquad (1)$$

The foliage BEF was calculated as

$$\mathrm{BEF}_{\mathrm{foliage}} = \frac{\Sigma\ (\text{foliage biomass of single trees in hypothetical stand})}{\Sigma\ (\text{stemwood biomass of single trees in hypothetical stand})} \qquad (2)$$

Each of these biomass components was computed for every tree in the hypothetical stand and then summed to the stand level (Penner et al. 1997).

In the northeastern United States, BEF for hardwoods was calculated as follows:

$$\mathrm{BEF} = \exp[1.912 - 0.34 \times \ln(\mathrm{GSVD})] \qquad (3)$$

where GSVD is the volume of growing stock per unit area ($\mathrm{m}^3\ \mathrm{ha}^{-1}$); if GSVD > 200 $\mathrm{m}^3\ \mathrm{ha}^{-1}$, BEF = 1.0 (Brown et al. 1999).

For spruce and fir, BEF was calculated as follows:

$$\mathrm{BEF} = \exp[1.77 - 0.34 \times \ln(\mathrm{GSVD})] \qquad (4)$$

Here, if GSVD >160 $\mathrm{m}^3\ \mathrm{ha}^{-1}$, BEF = 1.0 (Brown et al. 1999).

Understory Biomass Equations

For shrub (or sapling) understory biomass, allometric biomass equations are commonly used; these are similar to the equations for merchantable trees in Table 1. For example, an overall formula for all sapling species in Ontario was reported as follows:

$$B = 0.030 + 0.021\,107 D^2 H \qquad (5)$$

where B is the estimated sapling biomass (kg/tree), D is DBH (cm), H is tree height (m), and *a* and *b* are coefficients (Alemdag 1980).

In some circumstances where biomass equations are not available, a biomass constant has been used to roughly estimate shrub (or tree seedling) biomass. For instance, for woody plants with a height of 1.30 m or less, the average oven-dry biomass per seedling in the area of Petawawa, Ontario, was established as 0.008 kg for coniferous species, 0.009 kg for hardwood species with a height of 1.30 m, and 22 g/stem for coniferous species with a height of 0.81 m to 1.30 m (Alemdag 1980, 1982, 1984).

Belowground Biomass Estimation

For belowground biomass, the development of biomass equations has long been hampered by limited quantitative descriptions of root biomass dynamics. Compared with aboveground biomass equations, fewer root biomass equations have been reported, because most existing techniques to measure fine root biomass and production are controversial, time consuming, and labor intensive to develop. In some situations, the biomass of root components has been calculated from the allometric tree component biomass equations in Table 1. Nevertheless, belowground biomass has more frequently been deduced from the relation between belowground and aboveground component biomass. For example, the following equations have been widely used for the boreal forest of west-central Canada:

$$B_{\mathrm{r}} = a + bB_{\mathrm{a}} \qquad (6)$$

$$B_{\mathrm{r}} = e^{a}\,(B_{\mathrm{a}})^{b} \qquad (7)$$

where B_{r} is root biomass, B_{a} is aboveground biomass, and a and b are coefficients (Kurz et al. 1996; Li et al. 2003).

In some cases, a constant ratio of aboveground biomass to root biomass has been employed to approximate belowground biomass (Monserud et al. 2006). In cold temperate and subarctic zones, the biomass of roots ranges from 20% to 50% of the aboveground biomass (Kajimoto et al. 1999; Kort and Turnock 2000; Laclau 2003). In cold regions, for example, the ratios of roots to aboveground biomass for mature evergreen conifers have been reported as follows: 22.73% to 35.71% for *Pinus sylvestris* L. forests in the Siberian region, 45.45% for *Abies amabilis* Dougl. in subalpine forests, and 37.04% to 50.00% for *Pinus contorta* var. *latifolia* Engelm. in North America (Johnston et al. 1996; Kajimoto et al. 1999).

For understory root biomass, Johnston et al. (1996) reported that belowground biomass of shrubs accounted for 71.43% of total biomass (aboveground plus belowground), on the basis of results from studies in northern North America and Nordic countries, whereas the root biomass of herbs accounted for 83.33% of total biomass, on the basis of work carried out at the Cedar Creek Natural History Area in east-central Minnesota.

Litterfall Biomass Estimation

So far, only a few biomass equations have been published for estimating litterfall biomass. In Oklahoma, litterfall biomass was estimated by the following equations:

$$\mathrm{LF}_{p,t} = a + b\mathrm{LF}_{p,t-2} + c\mathrm{Temp}_{t-1} + d\mathrm{SI}_{p} + \varepsilon_{p,t} \qquad (8)$$

where $\mathrm{LF}_{p,t}$ and $\mathrm{LF}_{p,t-2}$ are total litterfall biomass (kg ha^{-1}) on plot p during growing seasons t and $t-2$; Temp_{t-1} is the arithmetic average of the temperatures in March, April, May, and June for the growing season in which the needles were produced ($t-1$); SI_{p} is the site index (m) (base age = 50 years old) of plot p; $\varepsilon_{p,t}$ is the unexplained error (kg ha^{-1}) for litterfall on plot p during the growing season; and a, b, c, and d are coefficients (Huebschmann et al. 1999). For needle litterfall of a shortleaf pine (*Pinus echinata* Mill.) stand in Oklahoma, the above equation was concretized as follows (Huebschmann et al. 1999):

$$\begin{gathered}\mathrm{LF}_{p,t} = -14\,248.784\,05 + 0.555\,661\mathrm{LF}_{p,t-2} + \\ 771.104\,886\mathrm{Temp}_{t-1} + 89.721\,631\mathrm{SI}_{p} \qquad (9) \\ (P < 0.0001)\end{gathered}$$

Extrapolation from Single-Tree Biomass to Stand Biomass

The following approaches have been reported for converting individual tree biomass to stand biomass in Canada and the northern United States.

Mean tree method: Stand biomass is estimated by harvesting and analyzing one or more representative trees. Sample tree data are converted to area by multiplying the biomass of individual sample trees by the average number of trees per unit area. This method has frequently been used for plantations and even-aged stands (Penner et al. 1997; Johansson 1999).

Stratified tree technique: This is a variant of the mean tree method for uneven-aged stands. The trees in a stand are stratified by diameter size classes, and the mean tree method is applied to each diameter class (Johansson 1999).

Normal distribution approach: Tree dimension (e.g., DBH or height) is assumed to be a normally distributed variable with mean equal to that of the typical dominant tree and variance equal to a specified value (e.g., a coefficient of variation of 20%). The sum of randomly generated individual tree biomass is used as an estimate of stand biomass (Penner et al. 1997).

Unit area method: All individual trees within randomly located plots are harvested. The measured biomass of the individual trees is converted to biomass per unit area (Yarie and Mead 1988; Johansson 1999).

Canopy area method: Sample tree biomass is converted to area, according to the proportion of the area occupied by the canopy projection of the sample trees (Alberta Forest Service 1985a, 1985b, 1988; Johansson 1999).

Basal area proportion method: This method is based on the ratio of stand basal area to sample tree basal area. The method includes three indices: current annual increment, dependent on the most recent annual radial increment of the stem; current periodic annual radial increment, based on the mean of the last 5 or 10 annual radial increments; and mean annual increment divided by the age of the sample trees (Johansson 1999).

Aboveground biomass conversion table method: Aboveground biomass is first estimated at the tree level using allometric relations, and measured stem distributions are subsequently summed to estimate plot-level biomass. Aboveground conversion tables are then computed from regression models that relate the plot-level biomass values to stand attributes (e.g., species composition) (Fournier et al. 2003).

It should be mentioned that the sampling method and estimation techniques are of less importance than the size of the sample plot; for sample plots covering 10% or more of total stand area, estimates converge toward the stand value (Madgwick 1991; Johansson 1999).

Materials and Methods

Selection of Biomass Equations

A total of 17 biomass equations for estimating overstory, understory, and belowground biomass were chosen on the basis of the following criteria: typical and commonly used in Canada or the northern United States (north of about 40°N), especially west-central Canada (Fig. 1); availability of parameter values for major forest species of west-central Canada; empirical, simple, and with relatively few variable parameters; and published in peer-reviewed journals or serials. If any coefficients of the equations were missing for the target study area (west-central Canada), the counterparts of the geographically closest site or adjacent ecozone were applied.

Table 2 lists the equations selected for this study, referred to by formula number. Formula 1 offers a good balance between accurate predictions and limited data requirements by measuring a DBH variable in forest studies (Ter-Mikaelian and Korzukhin 1997; Zianis and Mencuccini 2003).

Formulas 2, 3, and 4 were used in CanFI'91 to calculate tree biomass in the Prairie provinces (Alberta, Manitoba, and Saskatchewan) and in the Northwest Territories (Singh 1982, 1984a), and formulas 5 and 6 were adopted for estimating tree biomass in western Ontario (Alemdag 1982) and Quebec (Ouellet 1983), respectively.

Formula 7 is a national equation system developed from as many as 1769 sample trees from six geographic ecoregions across Canada to estimate the biomass of three tree components: stemwood, stem bark, and crowns (Table 3). Hereinafter, whole-tree biomass is considered equal to the sum of the biomass of these tree components (Evert 1985).

Figure 1. Map of the study area.

Table 2. Biomass equations selected for this study

	Formula[a,b]	Description and comments	Data requirement	DBH[c] (cm)	R^2[d]	SEE[e]	Sample size	Application limits	Reference
1	$B = aD^b$	Exponential through origin	DBH (cm)	1–32	0.626–0.998	0.10–12.70	8–195	Single tree and components	Ter-Mikaelian and Korzukhin 1997
2	$B = a + bD + cD^2 + dD^3$	Polynomial	DBH (cm)	0–31+	0.28–0.99	0.17–53.79	37–61	Single tree and components	Singh 1982, 1984a
3	$B = a + bD + cH + dD^2H + eD^2 + fD^3$	Polynomial and combined allometric variables through origin	DBH (cm), height (m)	0–31+	0.41–0.99	0.17–54.65	37–61	Single tree and components	Singh 1982, 1984a
4	$B = a + bD^2H$	Combined allometric variables	DBH (cm), height (m)	0–31+	0.00003–0.99	0.18–59.8	37–61	Single tree and components	Singh 1982, 1984a
5	$B = aD^2H$	Combined allometric variables through origin	DBH (cm), height (m)	5.2–35.8	0.167–0.993	8.3–114.5	66–128	Single tree and components	Alemdag 1980; Aldred and Alemdag 1988
6	$B = aD^bH^c$	Combined allometric and exponential variables through origin	DBH (cm), height (m)	0.0–34.6	NA[f]	NA	NA	Single tree and components	Alemdag 1982; Ouellet 1983
7a	$B = a + bD^2H + cD^3H + dD^4H$	Polynomial and combined allometric variables	DBH (cm), height (m)	0.1–40	NA	7.42–23.12	173–1769	Stem wood	Evert 1983, 1985
7b	$B = a + bD^2H + cD^{1.5}H + dD^2H^2 + eD^2H^4$ for white spruce, black spruce, and trembling aspen $B = a + bD^2H + cD^3H + dD^4H + eD^2H^2 + fD^2H^3$ for jack pine $B = a + bD^2H + cD^3H + dD^4H$ for lodgepole pine, balsam fir, balsam poplar, and white birch	Polynomial and combined allometric variables	DBH (cm), height (m)	0.1–40	NA	1.85–5.75	173–1769	Stem bark	

Table 2. Continued

	Formula[a,b]	Description and comments	Data requirement	DBH[c] (cm)	R^2[d]	SEE[e]	Sample size	Application limits	Reference
7c	$B = a + b\left(\frac{D^3}{H}\right) + c\left(\frac{D^3}{H}\right)^2 + d\left(\frac{D^3}{H}\right)^3 + e\left(\frac{D^3}{H}\right)^4$ for white spruce, black spruce, jack pine, balsam fir, lodgepole pine, and white birch $B = a + b\left(\frac{D^{2.9}}{H^{0.8}}\right) + c\left(\frac{D^{2.9}}{H^{0.8}}\right)^2 + d\left(\frac{D^{2.9}}{H^{0.8}}\right)^3$ for trembling aspen $B = a + b\left(\frac{D^{2.5}}{H}\right) + c\left(\frac{D^{2.5}}{H}\right)^2 + d\left(\frac{D^{2.5}}{H}\right)^3$ for balsam poplar $B = a + b\left(\frac{D^{2.5}}{H^{0.5}}\right) + c\left(\frac{D^{2.5}}{H^{0.5}}\right)^2 + d\left(\frac{D^{2.5}}{H^{0.5}}\right)^3$ for white birch	Polynomial and combined allometric variables	DBH (cm), height (m)	0.1–40	NA	10.11–18.92	173–1769	Tree crown	Evert 1983, 1985
8	$B = \frac{(a + bD^c)}{(D^c + d)}$	Exponential	DBH (cm)	1.3–85.1	0.98–0.99	NA	NA	Single tree	Brown et al. 1997, 1999
9a	$V = a + bD^bH^c$	Combined allometric and exponential variables	DBH (cm), height (m)	NA	NA	NA	NA	Single tree	Singh 1984b; Penner et al. 1997
9b	$B = aV^b$	Exponential through origin	Volume (m^3)	NA	0.93–0.99	NA	45–48	Single tree	Singh 1984b
10	$B = aX^b$	Exponential through origin	Age at breast height	NA	NA	NA	23–41	Tree shelterbelt	Kort and Turnock 2000
11	$B = 1.22D^2 H \times 10^{-2}$	Combined allometric variables through origin	DBH (cm), height (m)	4.0–26.0	0.95–0.99	0.000 001–0.000 005	27–462	Saplings 2–5 years old	Senelwa and Sims 1998
12a	$B = 0.030 + 0.021\,107\,D^2 H$	Combined allometric variables	Diameter at ground level (cm), height (m)	0.1–5.0	NA	NA	NA	Tree sapling	Alemdag 1980, 1982
12b	$B = 0.200 + 0.017\,793\,D^2 H$	Combined allometric variables	Diameter at ground level (cm), height (m)	≤5.0	NA	NA	NA	Tree sapling	Alemdag 1982

Table 2. Concluded

	Formula[a,b]	Description and comments	Data requirement	DBH[c] (cm)	R^2[d]	SEE[e]	Sample size	Application limits	Reference
13	$\ln(B) = (2.51 \pm 0.02)\ln(D) - (1.23 \pm 0.01)$	Logarithmic	Diameter at ground level (cm)	0.3–6.0	0.979	NA	392	Tree sapling	Freedman 1984
14a	$B_r = 0.222B_a$ for softwood	Linear	B_a	NA	0.799	NA	340	Stand or singe tree root biomass	Kurz et al. 1996; Li et al. 2003
14b	$B_r = \exp(0.45489)B_a^{\ 0.615}$ for hardwood	Exponential through origin	B_a	NA	0.562	NA	103	Stand or singe tree root biomass	Kurz et al. 1996; Li et al. 2003
15	$B_r = \exp[-1.059 + 0.884 \times \ln(B_a) + 0.284]$	Exponential	B_a	NA	0.84	NA	151	Stand root biomass	Cairns et al. 1997; Brown et al. 1999
16a	$B = \exp(a + b\ln(D))$	Exponential	DBH (cm)	≥ 2.5	0.018–0.029	NA	121–137	Single tree	Jenkins et al. 2003
16b	$\text{ratio} = \exp(a + \frac{b}{D})$	Exponential	DBH (cm)	≥ 2.5	0.018–0.029	NA	121–137	Single tree root biomass	Jenkins et al. 2003
17a	$B_r = \exp(0.257D + 6.01)/1000$	Exponential	DBH (cm)	0–10	0.94	0.145	15	Single tree root biomass	Laclau 2003
17b	$B_r = \exp(0.172D + 6.34)/1000$	Exponential	DBH (cm)	10–30	0.86	0.289	105	Single tree root biomass	Laclau 2003

[a] Formulas 1–10 have been commonly applied to calculate whole-tree and/or tree component biomass in Canada and the northern United States. Formulas 11–13 were developed for shrub (or tree sapling) biomass of major species in Canada and New Zealand. Formulas 14–17 were established for softwood and hardwood root biomass in west-central Canada, northern United States, and south Argentina.

[b] B = oven-dry biomass of whole tree or tree components which may include belowground parts or not (kg/tree or Mg ha^{-1}); B_a = aboveground oven-dry biomass of whole tree (kg/tree or Mg ha^{-1}); D = diameter outside bark at breast height (cm) for individual tree, or diameter outside bark at ground level (or stump level) (cm) for tree sapling and shrub; H = tree height (m); V = tree volume (m^3/stem); X = tree age (years) at breast height; B_r = belowground oven-dry biomass (kg/tree or Mg ha^{-1}); ratio = ratio of root component to total aboveground biomass (dry weight) for trees with diameters at breast height 2.5 cm and larger; and a, b, c, d, e, and f = regression parameters.

[c] DBH= diameter at breast height (cm).

[d] R^2 = coefficient of determination.

[e] SEE = standard error of estimate.

[f] NA = not available.

Table 3. Regression coefficients for national systems of tree component biomass equations[a] (Evert 1985)

Species	*a*	*b*	*c*	*d*	*e*	*f*	SEE %[b]	Mean	Sample size
Oven-dry biomass of total stemwood (kg/tree) (formula 7a)									
$B = a + bD^2 H + cD^3 H + dD^4 H$									
Jack pine	0.16	2.098 27E–02	–3.683 88E–04	4.495 51E–06			14.5	108.5	514
Lodgepole pine	NS[c]	1.598 68E–02	–9.736 53E–05	3.793 31E–06			20.7	111.7	289
Black spruce	0.20	1.935 30E–02	–2.650 00E–04	2.013 00E–06			13.8	53.8	1769
White spruce	0.40	1.533 98E–02	–1.401 77E–04	1.177 19E–06			19.8	82.8	1025
Balsam fir	0.18	1.516 93E–02	–1.612 84E–04	9.775 51E–07			13.8	64.7	799
Trembling aspen	0.12	1.227 41E–02	1.603 17E–04	–3.497 00E–06			18.2	79.9	1114
Balsam poplar	0.07	1.210 38E–02	–2.822 02E–05	–1.090 56E–06			18.3	74.0	173
White birch	0.25	1.866 97E–02	–9.481 66E–05	1.549 47E–06			17.2	77.7	693
Oven-dry biomass of total stem bark (kg/tree) (formula 7b)									
$B = a + bD^2 H + cD^3 H + dD^4 H + eD^2 H^2 + fD^2 H^3$									
Jack pine	0.10	1.999 57E–03	–5.457 14E–05	6.716 24E–07	3.548 19E–05	1.436 75E–06	21.5	8.9	514
$B = a + bD^2 H + cD^{1.5} H + dD^2 H^2 + eD^2 H^4$									
Black spruce	0.05	1.335 76E–03	7.267 87E–03	–6.972 25E–05	4.307 16E–08	NS	24.4	7.6	1769
White spruce	0.06	3.112 78E–04	7.871 55E–03	–1.427 08E–05	4.360 50E–09	NS	30.8	10.6	1025
Trembling aspen	0.04	3.573 75E–03	1.760 80E–03	–7.052 42E–05	6.174 75E–08	4.280 31E–02	32.3	17.8	1114
$B = a + bD^2 H + cD^3 H + dD^4 H$									
Lodgepole pine	0.16	2.494 61E–03	–5.357 90E–05	3.751 54E–07			27.6	9.5	289
Balsam fir	0.10	2.569 37E–03	–2.598 72E–05	3.217 92E–07			34.8	11.9	799
Balsam poplar	0.10	3.605 54E–03	–4.620 60E–05	3.792 61E–07			28.6	18.7	173
White birch	0.06	3.796 88E–03	–4.727 90E–05	4.174 81E–07			33.0	13.1	693

Table 3. Concluded

Species	a	b	c	d	e	f	SEE %[b]	Mean	Sample size
Oven-dry biomass of total crown (kg) (formula 7c)									
			$B = a + b\left(\frac{D^3}{H}\right) + c\left(\frac{D^3}{H}\right)^2 + d\left(\frac{D^3}{H}\right)^3 + e\left(\frac{D^3}{H}\right)^4$						
Jack pine	0.20	4.280 31E–02	–2.821 18E–06	NS	NS		59.2	22.9	514
Lodgepole pine	0.30	5.074 08E–02	–6.491 32E–06	–1.252 62E–10	NS		64.1	20.5	286
Balsam fir	0.80	4.401 73E–02	9.638 92E–06	–2.620 80E–09	NS		59.8	16.9	1721
Balsam poplar	1.00	5.250 74E–02	1.098 47E–06	–5.340 25E–10	NS		63.7	29.7	966
White birch	0.50	4.171 67E–02	8.832 11E–06	–4.369 73E–09	NS		58.7	24.3	799
			$B = a + b\left(\frac{D^{2.9}}{H^{0.8}}\right) + c\left(\frac{D^{2.9}}{H^{0.8}}\right)^2 + d\left(\frac{D^{2.9}}{H^{0.8}}\right)^3$						
Trembling aspen	0.10	3.016 51E–02	4.595 25E–06	–1.186 51E–09			74.5	17.4	1112
			$B = a + b\left(\frac{D^{2.5}}{H}\right) + c\left(\frac{D^{2.5}}{H}\right)^2 + d\left(\frac{D^{2.5}}{H}\right)^3$						
Balsam poplar	NS	6.679 15E–02	6.574 98E–04	–8.336 69E–07	NS	NS	69.7	15.3	170
			$B = a + b\left(\frac{D^{2.5}}{H^{0.5}}\right) + c\left(\frac{D^{2.5}}{H^{0.5}}\right)^2 + d\left(\frac{D^{2.5}}{H^{0.5}}\right)^3$						
White birch	0.50	5.026 11E–02	5.085 51E–05	–1.498 34E–08			57.8	26.6	693

[a] B = oven-dry biomass of the entire tree, tree components, or stand (kg/stem or Mg ha^{-1}), D = diameter at breast height (cm); H = tree height (m); and a, b, c, d, e, and f = regression parameters.
[b] SEE = Standard error of estimation.
[c] NS = Not significant at the confidence level of 95%.

Formula 8 was fitted with a sample data set consisting of 454 trees from 34 hardwood species (DBH 1.31–85.1 cm) and 83 trees from 5 conifer species (DBH 2.5–71.6 cm) in the northeastern United States. The equation can be used to calculate individual tree biomass of hardwoods and conifers, on the assumption that the biomass of different species of hardwood and softwood trees is the same or similar (Brown et al. 1997; Schroeder et al. 1997).

Formula 9 encompasses two steps for biomass estimation: first, individual tree volumes were calculated for major tree species by means of the volume equations employed in CanFI'91 (Table 4) (Penner et al. 1997), and then the estimated volume was extrapolated to single-tree biomass by the BEF equations for converting from volume to biomass (Table 5) (Singh 1984b).

Formula 10 depicts the relation of annual carbon accumulation and tree age at breast height of eight shelterbelt tree species in three soil types (black soil, dark brown soil, and brown soil) of Saskatchewan (Kort and Turnock 2000). The average biomass prediction of the three soil types was used (Table 6). The BEF for converting from amount of carbon to biomass was assumed to be 0.5 (Johnston et al. 1996; Fang et al. 2001).

Formulas 11, 12, and 13 were created to estimate shrub (or tree sapling) biomass for Canada and New Zealand. Formula 11 was used for sapling (or shrub) biomass of *Pinus radiata, Acacia dealbata,* and five species of eucalypts (swamp gum, *Eucalyptus ovata,* Labill.; Sydney blue gum, *E. saligna* Sm.; Tasmanian blue gum, *E. globulus* Labill.; shining gum, *E. nitens* Maiden; and Aka Mountain ash, *E. regnans* F. Muell.) in New Zealand (Senelwa and Sims 1998; Hall et al. 1975). Formula 12a was fitted for saplings of all tree species with DBH < 5 cm, whereas formula 12b was mainly for seedlings of four species in Ontario: jack pine, black spruce, white spruce, and balsam fir (Alemdag and Horton 1981; Alemdag 1982). Formula 13 was generated for all shrub species in eastern Canada (DBH 0.30–6.0 cm) (Freedman 1984).

Table 4. Individual tree volume equations for west-central Canada used in the 1991 Canada's Forest Inventory (Penner et al. 1997)

Province or territory	Tree species	Volume equations[a]
Alberta	White spruce	$V = 4.328\,336 \times 10^{-5} D^{1.882\,751} H^{1.024\,11}$
	Black spruce	$V = 4.328\,336 \times 10^{-5} D^{1.882\,751} H^{1.024\,11}$
	Jack pine	$V = 4.421\,585 \times 10^{-5} D^{1.926\,909} H^{1.003\,04}$
	Trembling aspen	$V = 7.491\,573 \times 10^{-5} D^{1.877\,086} H^{0.850\,270}$
	Lodgepole pine	$V = 4.421\,585 \times 10^{-5} D^{1.926\,909} H^{1.003\,04}$
	Balsam fir (also used for alpine fir)	$V = 7.491\,573 \times 10^{-5} D^{1.877\,086} H^{0.850\,270}$
	White birch	$V = 5.634\,793 \times 10^{-5} D^{1.976\,455} H^{0.803\,794}$
	Balsam poplar	$V = 2.472\,902 \times 10^{-5} D^{1.871\,307} H^{1.179\,970}$
Manitoba	White spruce	$V = -1.331 \times 10^{-3} + 3.292\,128 \times 10^{-3} (D^2 H)/100$
	Black spruce	$V = -1.030\,7 \times 10^{-2} + 3.361\,824 \times 10^{-3} (D^2 H)/100$
	Jack pine	$V = -1.625\,4 \times 10^{-2} + 3.424\,306 \times 10^{-3} (D^2 H)/100$
	Trembling aspen	$V = 4.276 \times 10^{-3} + 3.317\,746 \times 10^{-3} (D^2 H)/100$
	Balsam fir	$V = 4.276 \times 10^{-3} + 3.317\,746 \times 10^{-3} (D^2 H)/100$
	White birch	$V = -1.449\,6 \times 10^{-2} + 3.425\,386 \times 10^{-3} (D^2 H)/100$
	Balsam poplar	$V = -1.313\,9 \times 10^{-2} + 3.387\,226 \times 10^{-3} (D^2 H)/100$
	White spruce (submerchantable)	$V = 0.408\,552 D^2 H$
	Black spruce (submerchantable)	$V = 0.406\,110 D^2 H$
	Jack pine (submerchantable)	$V = 0.413\,375 D^2 H$
	White birch (submerchantable)	$V = 0.415\,959 D^2 H$
	Balsam fir (submerchantable)	$V = 0.407\,202 D^2 H$
Northwest Territories	White spruce	$V = 4.316 \times 10^{-2} + 3.152\,6 \times 10^{-5} D^2 H$
	Black spruce	$V = 4.32 \times 10^{-3} + 3.571\,8 \times 10^{-5} D^2 H$
	Jack pine	$V = 1.338\,7 \times 10^{-1} + 3.610\,6 \times 10^{-5} D^2 H$
	Trembling aspen	$V = 4.591 \times 10^{-1} + 3.113\,3 \times 10^{-5} D^2 H$
	Balsam poplar	$V = -1.008 \times 10^{-2} + 2.925\,4 \times 10^{-5} D^2 H$

[a] All volumes are total volumes unless otherwise indicated; V = volume (m^3); D = diameter at breast height (cm); H = height (m).

Table 5. Regression coefficients for formula 9b, converting green merchantable volume (m^3) into oven-dry weight (kg) for 10 species in the Alberta prairies (Singh 1984b)

Species (entire tree with foliage)	Sample size	a	c	R^{2a}
Balsam fir	47	444.532	0.873 007	0.93
Balsam poplar	46	421.342	0.877 980	0.96
Black spruce	47	516.226	1.001 660	0.98
Jack pine	48	477.288	0.983 019	0.98
Lodgepole pine	48	436.564	0.962 308	0.99
Trembling aspen	47	499.508	0.980 765	0.98
White birch	45	703.360	0.946 751	0.93
White spruce	46	451.544	0.958 852	0.98

[a] R^2 = coefficient of determination.

Table 6. Regression coefficients for annual carbon accumulation (formula 10) for eight shelterbelt species in Saskatchewan (Kort and Turnock 2000)

		Black soil zone		Dark brown soil zone		Brown soil zone	
Tree species	Sample size	a	b	a	b	a	b
Green ash	30	1.1391	0.2932	0.7284	0.2932	0.5218	0.2932
Manitoba maple	23	0.1177	1.0568	0.0654	1.0568	0.0916	1.0568
Poplar	26	0.7679	0.9651	0.3232	0.9651	0.2089	0.9651
Siberian elm	31	2.6801	0.2551	2.0672	0.2551	1.6595	0.2551
Colorado spruce	26	1.0394	0.4560	0.9950	0.4560	0.8193	0.4560
White spruce	41	0.2318	0.8960	0.1345	0.8970	0.1633	0.8970
Scots pine	37	0.3159	0.6716	0.2895	0.6716	0.2266	0.6716
Caragana	NA[a]	0.5987	0.6446	0.4511	0.6446	0.4017	0.6446

[a] NA = not available.

Formulas 14a and 14b indicate a relation between root and shoot biomass for softwood and hardwood species of the temperate and boreal forest in western Canada, respectively (Kurz et al. 1996; Li et al. 2003). Formulas 15 and 16 delineate the estimates of root biomass of multiple species and ages at the stand level (Brown et al. 1999; Jenkins et al. 2003), whereas formula 17 was originally developed for ponderosa pine (*Pinus ponderosa* (Dougl.) Laws.) in Patagonia, Argentina (Laclau 2003).

Test Data Set

Parameter values for a given biomass equation are usually estimated by linear or nonlinear regression on the basis of a specific data set collected from a given region and are thus the best estimates for characterizing the given data set. However, they may not be the best estimates for data sets collected from other regions. This raises the question of whether such biomass equations can reasonably be used for estimating the biomass of a large spatial unit encompassing areas outside the region where the equation was originally developed.

There are two approaches to answering this question. One is to collect empirical data across the entire large spatial unit and to re-estimate the parameter values on the basis of the new data set. This approach is straightforward but requires considerable time and resources. The second approach is to evaluate the relative bias associated with using the original biomass equation to estimate biomass under various conditions. This can be done with a standard test data set that encompasses a wider range of conditions. This approach is not designed to generate the best estimates for a given biomass equation; however, it does allow identification of the existing biomass equations that will provide the biomass estimates with the lowest bias under various conditions. This approach, which is less expensive than the first approach, was used in the current study.

To consistently evaluate the selected biomass equations, a standard test data set was synthesized to represent the average growth of major boreal forest species at a large spatial scale in west-central Canada; the test data set was based on the published literature for boreal forest yield tables and biomass production in west-central Canada (Table 7) (Alemdag 1980; Cannell 1982; Evert 1983; Bonnor 1985; Alberta Forest Service 1985a, 1985b, 1988; Alaback 1986; Aldred and Alemdag 1988; Yarie and Mead 1988; Huang and Titus 1992; Kurz et al. 1992; Lowe et al. 1996; Gray and Power 1997; Penner et al. 1997; Thysell and Carey 2000; Tremblay and Larocque 2001; Solomon and Zhang 2002; Yang and Titus 2002). In brief, an effort was made to collect the published data for the growth of major tree species at the large spatial scale of west-central Canada and to use the averages of these data as the test data set. This test data set was then used for calculating biomass dynamics at the individual tree and stand levels.

Table 7. Characteristics of test data set used in current study[a]

Level	DBH (cm)[b]	Tree height (m)	Stand age[c] (years)	Stand density (stems/ha)
1	<5.0	<5.0	<5 (regeneration/ reproduction)	>8 100
2	5.0	5.0	15 (regeneration/young: 1–20)	8 100
3	10.0	10.0	40 (immature: 21–60)	2 200
4	20.0	15.0	60 (immature: 21–60)	1 000
5	30.0	20.0	80 (mature: 61–100	450
6	≥40.0	≥25.0	≥140 (overmature: 100–180)	≤200

[a] This test data set was integrated on the basis of published literature for boreal forest yield tables and biomass production in west-central Canada (Alemdag 1980; Cannell 1982; Evert 1983; Bonnor 1985; Alberta Forest Service 1985b, 1988; Alaback 1986; Aldred and Alemdag 1988; Yarie and Mead 1988; Huang and Titus 1992; Kurz et al. 1992; Lowe et al. 1996; Gray and Power 1997; Penner et al. 1997; Thysell and Carey 2000; Tremblay and Larocque 2001; Solomon and Zhang 2002; Yang and Titus 2002).

[b] DBH = diameter at breast height (cm).

[c] Where there are two terms separated by a slash within parentheses, the first is from Alberta Forest Service (1985b, 1988), and the second is from Gray and Power (1997).

The data set consisted of four variables: DBH, tree height, stand age, and stand density. All of the variables had six levels, which were extrapolated from the means of the published field experimental data or inventory data. For example, DBH was roughly grouped into categories of <5.0, 5.0, 10.0, 20.0, 30.0, and ≥40.0 cm and height into categories of <5.0, 5.0, 10.0, 15.0, 20.0, and ≥25.0 m, which were deduced from averages of the published field survey data for major species of the west-central Canadian boreal forest (Cannell 1982; Alberta Forest Service 1985a, 1985b, 1988; Huang and Titus 1992; Gray and Power 1997; Hogg and Schwarz 1999). In Alberta, for example, the DBH and height of white spruce, black spruce, jack pine, balsam fir, trembling aspen, and white birch from field surveys ranged from 1.10 cm to 89.00 cm and from 1.70 m to 38.40 m, respectively, and the average varied between 18.01 and 26.41 cm and between 12.20 and 20.09 m, respectively (Huang and Titus 1992).

In the data set, stand age was determined from CanFI'91 and the Alberta Phase 3 Forest Inventory, where it was classified as regeneration, immature, mature, and overmature, and reproduction, young, immature, mature, and overmature, respectively (Alberta Forest Service 1985b, 1988; Gray and Power 1997).

The density data for the test stand were integrated from field survey data for Alberta (Cannell 1982; Alberta Forest Service 1985a, 1988; Gray and Power 1997) and the estimates of two self-thinning lines (Fig. 2), because sometimes the roles of stand self-thinning in silviculture were not sufficiently reflected by the survey data:

$$\mathrm{QMD} = 1/(a + b\mathrm{DEN}^{c}) \qquad (10)$$

$$\ln(\mathrm{QMD}) = 6.90 - 0.53 \ln(\mathrm{DEN}) \qquad (11)$$

where QMD is the quadratic mean tree diameter and DEN is the number of trees per unit area. Here, equation 11 was developed for Alberta mixedwood (Yang and Titus 2002), and equation 12 was fitted for mixed softwood in the northeastern United States (Solomon and Zhang 2002).

In the data set, these four variables (DBH, tree height, stand age, and stand density) roughly corresponded to each other for every level (see Table 7) (Alberta Forest Service 1985a, 1985b, 1988; Huang and Titus 1992; Kurz et al. 1992; Gray and Power 1997).

For the test data set, the single-tree biomass of six major species (white spruce, jack pine, trembling aspen, balsam fir, black spruce, and white birch) was calculated using formulas 1–10, shrub understory biomass was calculated with formulas 11–13, and belowground biomass was calculated using formulas 14–17.

It is noteworthy that the formulas for individual tree biomass were calibrated with the entire range of tree dimensions (i.e., DBH and tree height) to evaluate their applicable limits.

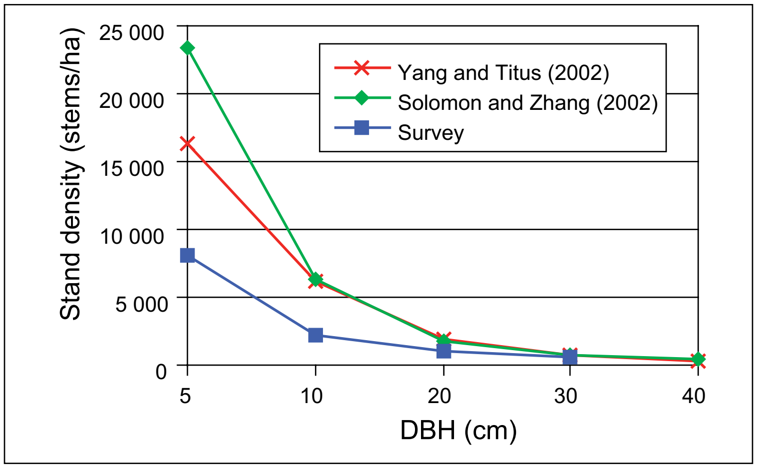

Figure 2. **Predicted and observed stand density of white spruce.** The observed data are based on stand density of white spruce in Alberta phase 3 forest inventory (Alberta Forest Service 1985b).

Identification of Appropriate Biomass Equations

A confidence interval of ±10% for the means of biomass estimates was used to identify the average and general biomass formulas for boreal forests in west-central Canada. For different species, different biomass equations may fall within the confidence interval. For all six major species, the response functions with the highest frequency of biomass estimates falling within the confidence interval will represent the average and low-bias equations.

Comparison of Two Methods for Converting from Single-Tree Biomass to Stand Biomass

Two widely used methods for extrapolating from single-tree biomass to stand biomass were compared: the mean tree method and the normal distribution approach. For the mean tree method, the hypothetical even-sized stand biomass was equal to the individual tree biomass multiplied by stand densities for each level in Table 7. For the normal distribution approach, tree dimensions such as DBH and height were assumed to be normally distributed, a hypothetical 1-ha "stand" was randomly generated using the normal distribution function with the mean of DBH and height per level and a coefficient of variation (CV%) of 20%. The generated distribution was truncated to avoid negative random values for DBH and tree height. Stand biomass was equal to the sum of generated biomass for individual trees in the hypothetical 1-ha stand.

Biomass estimates for stand overstory determined by the above two methods were objectively calibrated with the productivity class II (capable of producing a merchantable stand within a reasonable length of time) of Alberta forest, and the stand understory biomass was objectively compared to the productivity class I (incapable of producing a merchantable stand within a reasonable length of time) of the prairie plains of Alberta in CanFI'91.

Results

Estimates of Individual Tree Biomass

For all six species, estimates of individual tree biomass increased over DBH in the shape of an exponential curve, and there were great variations in biomass estimates between the different equations for a given DBH (Fig. 3). For a large tree, with DBH of 40 cm, for instance, the biomass estimates varied from 382.46 kg/tree (formula 9) to 984.40 kg/tree (formula 8) for trembling aspen, from 370.80 kg/tree (formula 9) to 822.14 kg/tree (formula 8) for jack pine, from 326.13 kg/tree (formula 9) to 822.14 kg/tree (formula 8) for white spruce, from 187.38 kg/tree (formula 6) to 822.14 kg/tree (formula 8) for balsam fir, from 371.24 kg/tree (formula 9) to 822.14 kg/tree (formula 8) for black spruce, and from 521.32 kg/tree (formula 9) to 1121.88 kg/tree (formula 1) for white birch. Biomass estimates obtained with different equations may differ by a factor of more than two for a given DBH.

The absolute differences in biomass estimates increased along with DBH. For example, the standard deviations of biomass estimates generated by various equations increased with both DBH (in particular) and height for six species (Fig. 4). For large trees, with DBH 40 cm, the standard deviations for the six species varied within 136.39 for black spruce and 222.42 for white spruce, whereas for small trees, with DBH 5 cm, the standard deviations ranged from 2.74 for trembling aspen to 10.66 for black spruce. Therefore, between various biomass equations, there was greater possible variation in biomass estimates for large trees than for small trees.

For small trees, the relative differences in biomass estimates between various equations were fairly significant, although the variations in absolute terms were smaller. For example, for a small tree, with DBH 5 cm, the biomass estimates from formulas 1–10 ranged from 0.53 kg/tree

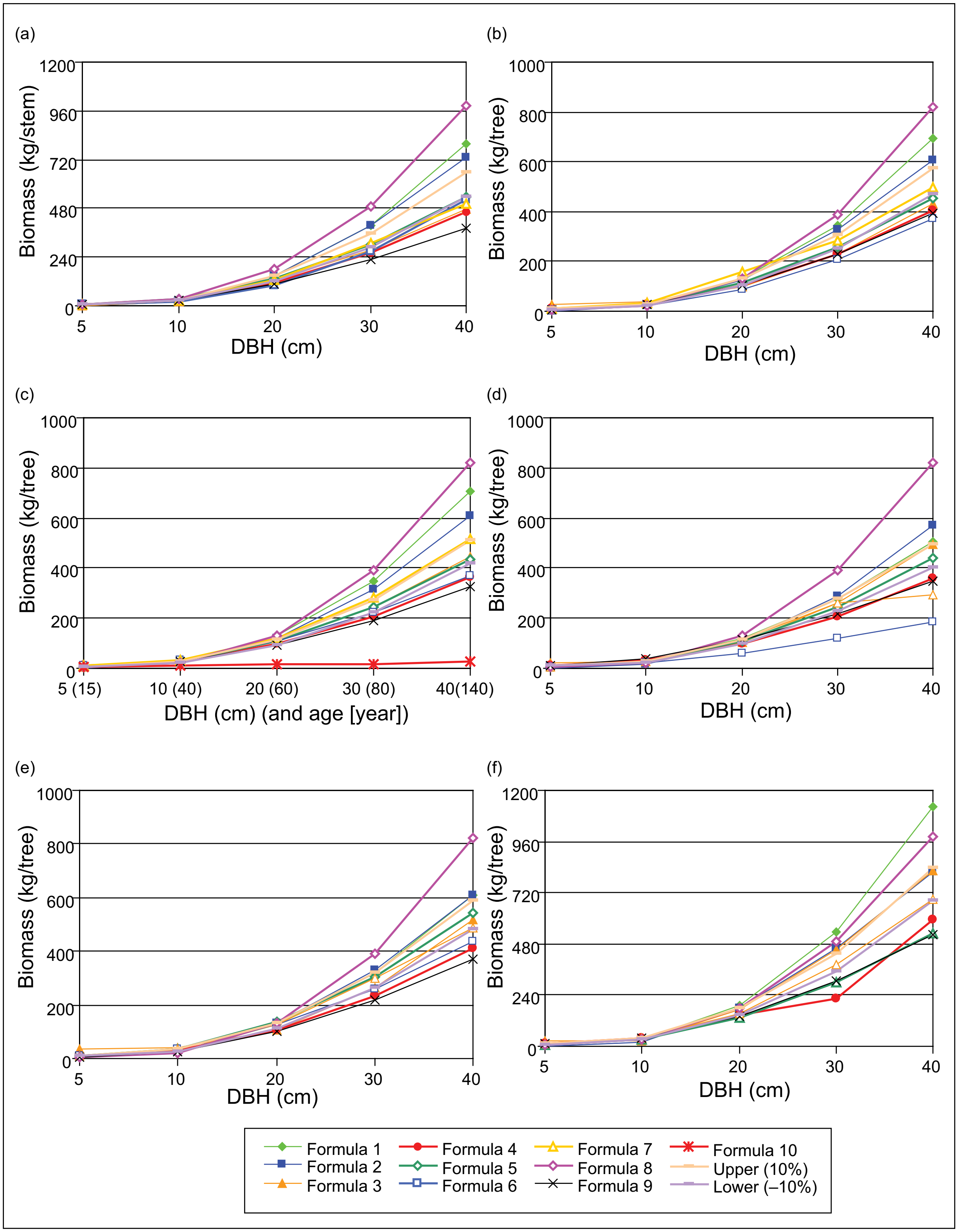

Figure 3. **Individual tree biomass predictions over diameter at breast height (DBH) for (a) trembling aspen, (b) jack pine, (c) white spruce, (d) balsam fir, (e) black spruce, and (f) white birch for fixed tree height (15 m).** Upper (10%) and lower (–10%) mean the upper and lower bounds of the 10% confidence interval for the mean of the estimates.

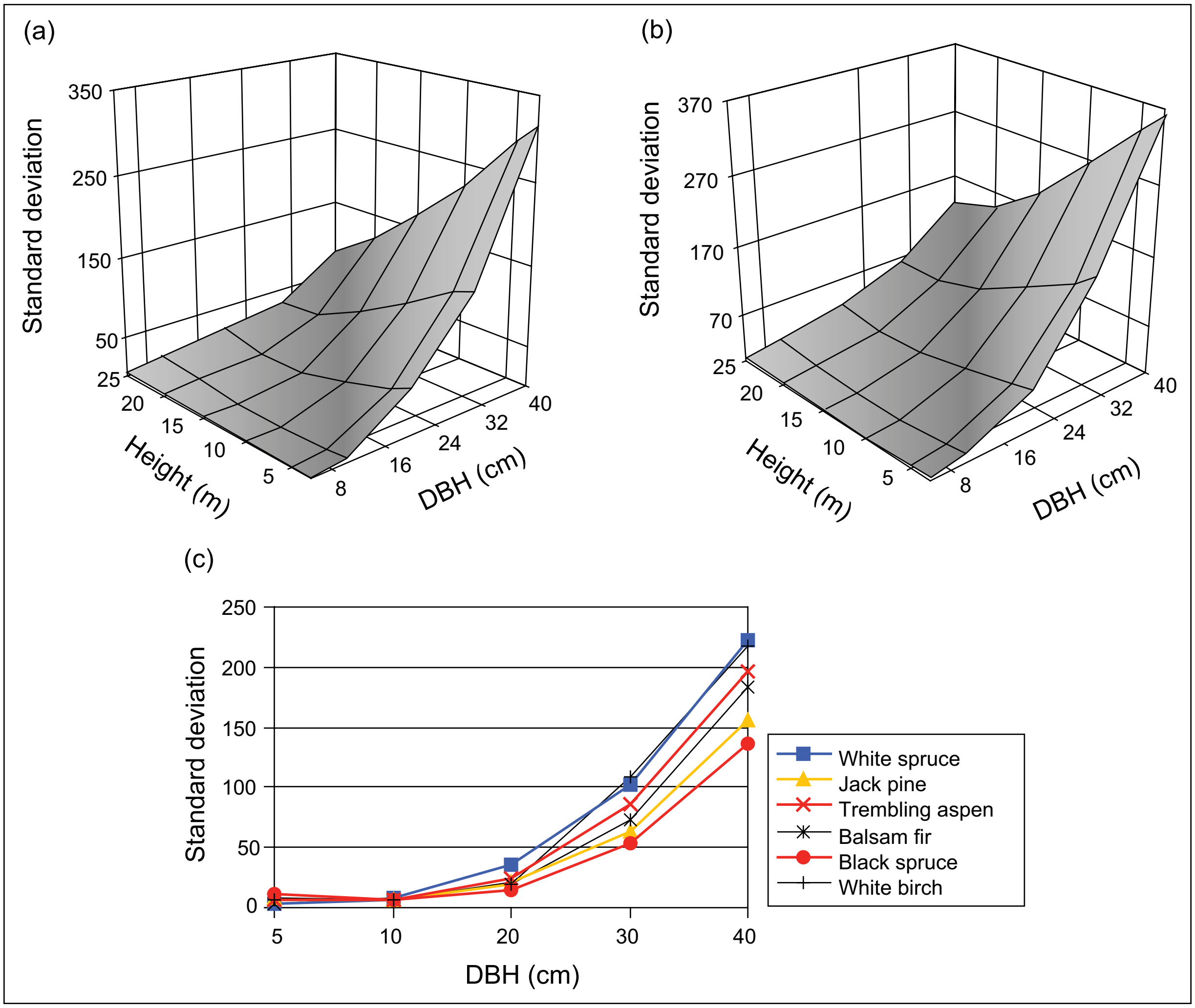

Figure 4. Standard deviation response surface of individual tree biomass estimates for (a) white spruce and (b) trembling aspen and (c) standard deviation of individual tree biomass estimates over diameter at breast height (DBH) for six species.

(formula 3) to 8.32 kg/tree (formula 9) for trembling aspen, from 2.46 kg/tree (formula 2) to 29.32 kg/tree (formula 3) for jack pine, from 2.43 kg/tree (formula 2) to 10.31 kg/tree (formula 6) for white spruce, from 2.51 kg/tree (formula 2) to 24.21 kg/tree (formula 3) for balsam fir, from 2.87 kg/tree (formula 2) to 38.05 kg/tree (formula 3) for black spruce, and from 2.21 kg/tree (formula 2) to 25.32 kg/tree (formula 3) for white birch. Consequently, for small trees, the discrepancy between maximum and minimum biomass estimates among formulas 1 to 10 was a factor of 15.70 for trembling aspen, 11.92 for jack pine, 4.24 for white spruce, 9.65 for balsam fir, 13.26 for black spruce, and 11.46 for white birch.

Compared with other equations for individual tree biomass, formula 10 yielded considerably lower values (Fig. 3c), probably because the formula was originally developed for estimating the biomass of shelterbelt trees in Saskatchewan, and such trees are usually smaller than normal forest wood. Thus, formula 10 appeared inapplicable for calculating the biomass of normal trees. This result conforms with those of previous studies of woodland areas that included both softwood and hardwood with lower biomass values at a given DBH (Jenkins et al. 2003).

Variations in Biomass Estimation

As mentioned above, although the differences in biomass estimates in absolute terms increased exponentially with tree dimensions (Fig. 4), the relative differences (i.e., coefficients of variation) in biomass estimates were lowest for the medium-sized trees, with DBH 10–15 cm and height 10–15 m (Fig. 5). For example, for small trees (e.g., 5 cm DBH, 5 m high) and large trees (e.g., 40 cm DBH, 25 m high), the CV% of biomass estimates ranged from 49.94% to 33.26% for white spruce and from 74.73% to 32.65% for trembling aspen; for medium-sized trees (10 cm DBH, 10 m high), the CV% of biomass estimates ranged from 11.00% for white spruce to 20.55% for trembling aspen. Therefore, the allometric biomass equations usually provided more consistent and reliable estimates for medium-sized trees than for small and large trees.

Figure 6 illustrates the response surface of average biomass estimates for white spruce and trembling aspen over DBH and height. Biomass estimates at the individual tree level usually increased with tree dimension, regardless of DBH and tree height. However, biomass responded more rapidly to DBH than to tree height, because the relation between biomass and DBH is generally exponential, whereas that between biomass and height is linear. Therefore, tree biomass calculations were more sensitive to DBH than to tree height, and therefore more precision in DBH measurement is required when sampling trees.

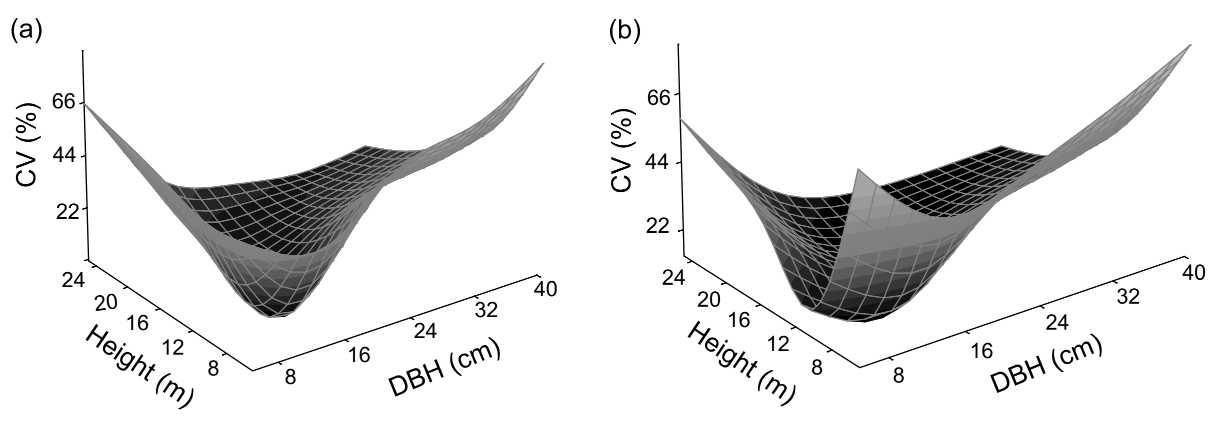

Figure 5. Coefficient of variation (CV) of individual tree biomass estimates for (a) white spruce and (b) trembling aspen.

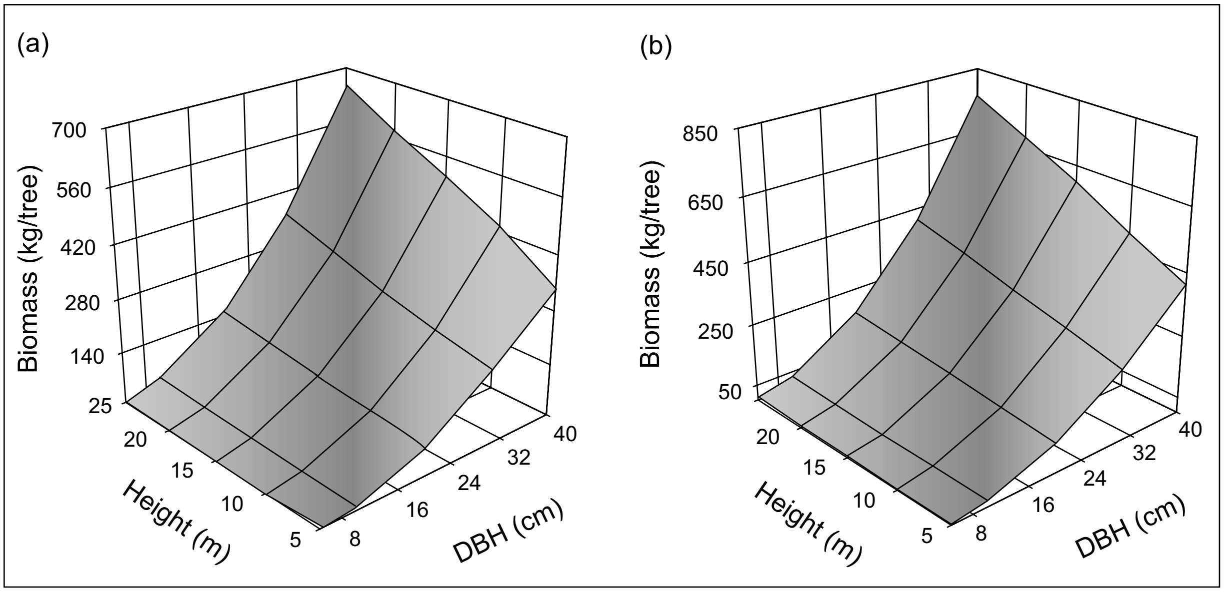

Figure 6. Response surface of mean individual tree biomass predicted by formulas 1–10 over diameter at breast height (DBH) and tree height for (a) white spruce and (b) trembling aspen.

Identification of Single-Tree Biomass Equations

Among the 10 single-tree biomass equations (formulas 1–10), the estimates of formulas 5 and 7 for trembling aspen, formula 7 for jack pine, formulas 3, 5, and 7 for white spruce, formulas 3 and 5 for balsam fir, formulas 3, 7, and 5 for black spruce, and formulas 3 and 7 for white birch almost fell within the confidence interval of ±10% for the means of biomass estimates (Fig. 3). Therefore, formulas 3, 5, and/or 7 can be considered the most appropriate for estimating individual tree biomass of the boreal forest in west-central Canada, because of the low risk of misestimation and the high chance of falling within the confidence interval. Moreover, these formulas were developed either exclusively for the Prairie provinces or generally for the Canadian national scale (Evert 1983, 1985; Singh 1984a; Aldred and Alemdag 1988). This conclusion conforms with previous reports that for biomass estimation at large scales, it is best to use a set of biomass equations that applies equally well to every stem across the region of interest and that such equations would be "generalizable," in that they would be applicable, for the purposes of broad-scale biomass estimation, to trees growing anywhere in the region (Jenkins et al. 2003). The results were also in agreement with previous studies suggesting ways to circumvent the problems of applying biomass equations across different ecosites: calibrate and validate some potential biomass equations with local sample data, or fit a new equation to the sample data, if such are available; find the regression parameters of several reported equations for the geographically closest site, and use the reported equations to estimate the range of biomass; and generate the biomass data used for various published equations, and fit a new equation to the generated data, if sample data are unavailable (Ter-Mikaelian and Korzukhin 1997; Jenkins et al. 2003).

Conversion of Stand Biomass

There were no significant differences in conversion to stand biomass between the mean tree method and the normal distribution approach. Figure 7 shows the stand biomass of white spruce and trembling aspen derived with each of these methods by multiplying the individual tree biomass estimates of formulas 3 (for white spruce) and 5 (for trembling aspen) by the stand densities in Table 7. With the normal distribution and mean tree techniques, stand biomass estimates of white spruce reached as high as 137.13 and 130.51 Mg ha^{-1} for a hypothetical stand with mean DBH 30 cm and average height 20 m. These results were slightly higher than the upper bound of biomass productivity class II of the Alberta forest in CanFI'91 (57–114 Mg ha^{-1}). For a hypothetical trembling aspen stand with mean DBH 30 cm and average height 20 m, the biomass estimates were 181.93 and 182.10 Mg ha^{-1} for the normal distribution and mean tree techniques, respectively. These results were significantly higher than those for the productivity class II of Alberta forest, probably because stand biomass in the current study was extrapolated for a hypothetically pure and roughly even-sized stand, whereas the field survey data were from an uneven-sized mixedwood stand (Gray and Power 1997; Penner et al. 1997).

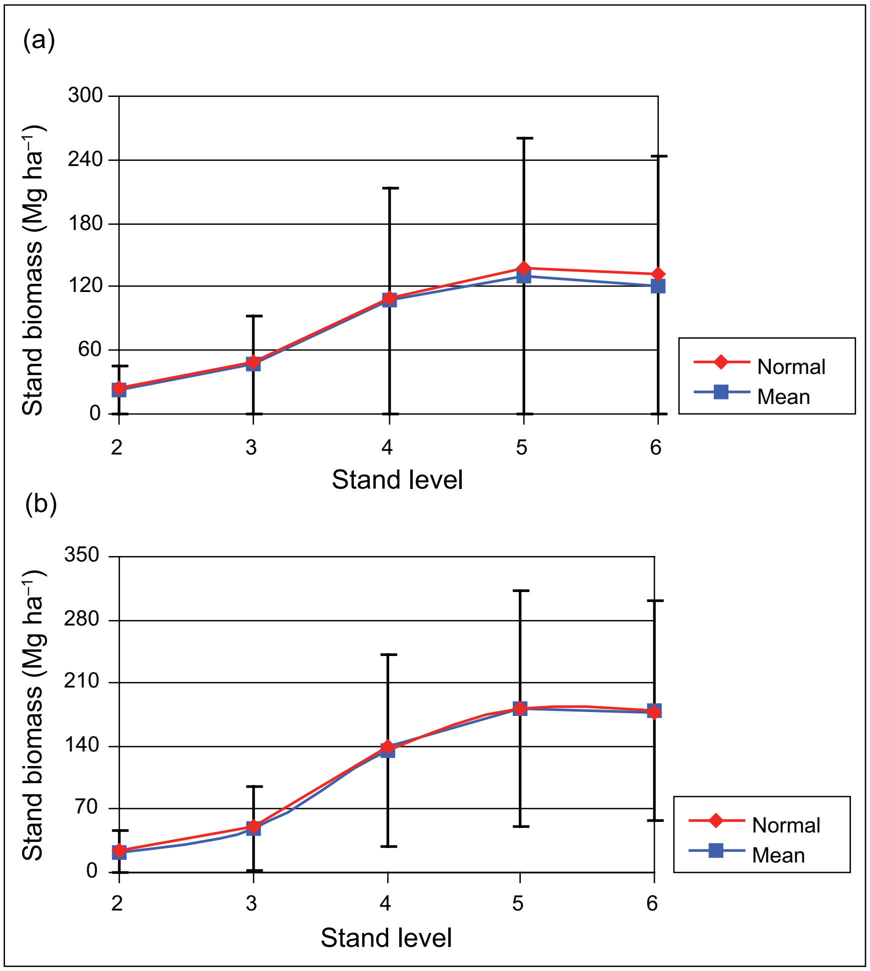

Figure 7. Stand biomass estimates for (a) white spruce and (b) trembling aspen in west-central Canada. Normal = normal distribution method of conversion, mean = mean tree method.

Estimation of Understory and Belowground Biomass

There were no significant differences in shrub (or tree seedling) biomass estimates among formulas 11–13, when shrub (or tree seedling) diameter at ground level was less than 3 cm. For shrub DBH > 3 cm, the estimates of formula 13 were significantly greater than those of the other formulas. For small shrubs (or tree saplings) (diameter at ground level < 3 cm), the estimates of formulas 11–13 conformed approximately with previous reports of shrub biomass constants: 0.022 kg/stem for tree seedling height 0.81 to 1.30 m for all species in the Petawawa area and 0.042 and 0.153 kg/stem for four major species (jack pine, black spruce, white spruce, and balsam fir) with height 0.31–0.80 m and 0.81–1.3 m in the Chalk River area, respectively (Alemdag 1980, 1982). For instance, for a tree seedling with diameter at ground level 1 cm and height 1 m, the predictions of formulas 11, 12a, 12b, and 13 were 0.012, 0.051, 0.218, and 0.059 kg/stem (Fig. 8), which are similar to the shrub biomass constants mentioned above.

For belowground biomass, differences in biomass estimates among formulas 14–17 were not significant for small or medium-sized trees (< 20 cm DBH) (Table 8). The average of single-tree aboveground biomass estimates from formulas 1–10 was applied to calculate belowground biomass of major species, specifically white spruce, jack pine, balsam fir, and trembling aspen. For white spruce with DBH 20 cm, for instance, the belowground biomass estimates included 22.18 kg/tree (formula 16), 22.71 kg/tree (formula 14a), and 27.56 kg/tree (formula 15). For white spruce, jack pine, and balsam fir, the estimated ratios of belowground to aboveground biomass were 22.2% for formula 14a, 22.3–37.5% for formula 15, and 21.3–23.9% for formula 16. For trembling aspen, the predicted ratio ranged from 13.4% to 83.9% for formula 14b, from 21.93% to 37.8% for formula 15, and from 18.8% to 21.7% for formula 16. These results were in agreement with previous studies, in which the proportion of root to total biomass ranged from 18% to 50% for various tree species at cold sites in North America (Johnstone 1972; Kurz et al. 1992; Kajimoto et al. 1999; Kort and Turnock 2000; Coble et al. 2001; Laclau 2003; Li et al. 2003).

However, formula 17 significantly overestimated belowground biomass of the large trees (>20 cm DBH). These results confirmed the application limits for this formula, whereby formulas 17a and 17b are applicable only to 10-year-old and 20-year-old stands, respectively (Laclau 2003).

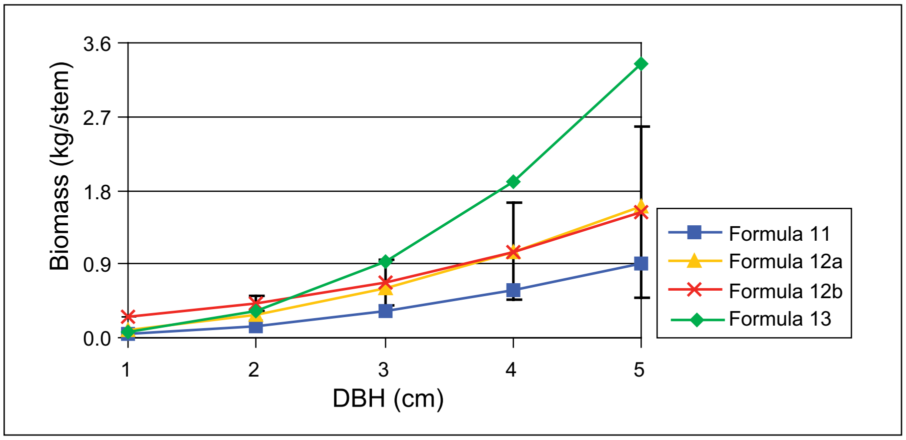

Figure 8. Tree sapling or shrub understory biomass predictions.

Table 8. Belowground biomass estimates for major forest species in west-central Canada

	DBH category; biomass (kg/tree)					
Tree species	Formula[a]	5 cm	10 cm	20 cm	30 cm	40 cm
White spruce	18a	1.30	5.21	22.71	54.81	102.69
	19	2.20	7.50	27.56	60.04	104.58
	20	1.40	5.26	22.18	52.94	98.63
	21a	1.47	5.32	69.56	908.91	11 875.64
	21b	1.34	3.17	17.68	98.72	551.28
Jack pine	18a	1.92	6.02	26.24	61.41	115.29
	19	3.10	8.52	31.30	66.38	115.84
	20	2.07	6.08	25.62	59.31	110.74
	21a	1.47	5.32	69.56	908.91	11 875.64
	21b	1.34	3.17	17.68	98.72	551.28
Balsam fir	18a	2.04	5.77	23.50	55.87	99.36
	19	3.27	8.21	28.40	61.06	101.57
	20	2.20	5.83	22.95	53.96	95.44
	21a	1.47	5.32	69.56	908.91	11 875.64
	21b	1.34	3.17	17.68	98.72	551.28
Trembling aspen	18b	4.31	11.79	31.76	55.13	80.52
	19	1.96	8.31	34.54	76.29	131.53
	20	1.18	5.27	25.36	61.32	112.78
	21a	1.47	5.32	69.56	908.91	11 875.64
	21b	1.34	3.17	17.68	98.72	551.28

[a] Average aboveground biomass estimates of formula 1–9 are used by formulas 18–20, respectively, to estimate root biomass.
DBH = diameter at breast height (cm).

Discussion

Accuracy of Biomass Equations

Although precision is needed to draw well-founded conclusions, it is insufficient to stress only this factor in appraising the application of biomass equations at different sites. For instance, "good" or even "best" estimates of biomass equations that have been calibrated and validated for one site cannot be directly applied to another site, because of site and species differences and variations associated with sampling, field measurements, or the predictor variables of biomass equations. Even if biomass equations have a high confidence level (i.e., high coefficient of determination [R^2] and low standard error of estimation [SEE]), biomass equations cannot be interpolated or extrapolated directly and reliably for different periods or sites for which measurements are not available. In addition, the R^2 and SEE values of biomass equations cannot be compared directly because of differences in regression-fitting methods, since the confidence level of an equation is strongly related to the regression methods, sample size, and quality of the sample data in the original study. As a consequence, the confidence level (e.g., $P < 0.0005$ or $P < 0.0001$) of an equation reveals only the degree of goodness-of-fit of the equation to its original sample data and fitting methodology. The R^2 and SEE do not show how well the equation fits at other sites, and sometimes the R^2 and SEE of biomass equations are meaningless for other sites.

The large potential sources of error in the biomass equations for one site represent a substantial obstacle for their application to other sites, but in practice it is nearly impossible to quantify all of these errors. Potential sources of error in allometric biomass estimations are abundant, and these are generally statistical errors associated with the estimated coefficient and the method of selecting the equation form; inconsistencies in sampling standards and methods; and diversity in biomass definition, measurement accuracy, and reporting protocols among the published biomass studies. One or more sources of error may simultaneously contribute to error or bias in estimates. Furthermore, potential errors and bias could be multiplied when biomass estimates at the individual tree level are converted to the stand scale. It is thus very difficult, if not impossible, to distinguish and identify the sources of error in biomass equations (Madgwick 1991; Jenkins et al. 2003).

Many authors have pointed out that the evaluation of biomass equations should concentrate on the special conditions of the study area and the objectives of the proposed study (Ter-Mikaelian and Korzukhin 1997; Wegehenkel 2000), but in practice this approach has been hindered by the availability of high-quality data sets. For example, for the purpose of calibrating biomass equations, a large local, independent, high-quality data set may theoretically allow the best evaluation of biomass equations at a given site. In particular, if a large quantity of representative temporary and permanent sample plot network data are available for trees of entire size classes, calibration with the local network data set would ensure unbiased appraisal of biomass equations in the area. However, it is expensive, labor intensive, and time consuming to do representative network tree sampling, especially for a large spatial area and entire range of size classes. Furthermore, it is difficult to obtain such raw data from the existing literature, because they are usually not published. Even for the limited raw data that are available, it would be difficult to ensure that the accumulated biomass data from the published studies represent all conditions, all species, and entire size classes across the study area in proportion to their occurrence in the forest (Jenkins et al. 2003). Therefore, the appraisal method with a certain confidence interval (e.g., ±10%) for the mean of the estimates may be accepted as an alternative way to quickly assess a general equation for a large spatial area, since it is simple and inexpensive, and saves labor and time.

Selection of Appropriate Single-Tree Biomass Equations for a Large Spatial Scale

Variations in predictions from one equation to another make it extremely difficult to accurately estimate tree biomass. As biomass equations are highly specific to site, size, and species, their uncertainties are also strongly dependent on site, species, and stand age and structure. Thus, when a user plans to adopt an equation to estimate forest biomass at the individual tree level, the effects of topography, site index, and tree dimensions on biomass dynamics should be taken into account. To the extent possible, an equation for the same tree species under geographically similar site conditions or at an adjacent site should be selected (Ter-Mikaelian and Korzukhin 1997). If equations are not available exclusively for a given site and species, equations for the same species in similar ecozones are recommended, although within-species variation of biomass estimates (i.e., variation among biomass regressions published by different authors for a given species) may sometimes exceed variation between species (Jenkins et al. 2003). That is why in this study, the application area (Canada or the northern United States, especially west-central Canada) was the first criteria for selecting the biomass equations. In addition, between-species variation in biomass estimates, although important, was excluded from this analysis.

The method of applying a confidence interval to the mean of the estimates was used to identify an average and low-bias equation, which resulted in a misestimate rather than the most accurate equation. For example, according to this approach, formulas 3, 5, and 7 were viewed as the most appropriate for estimating individual tree biomass of six boreal forest species in west-central Canada. These three equations, especially formula 7, were fitted with large sample data sets for each species, for sampling sites distributed over the Prairie provinces (Alberta, Saskatchewan, and Manitoba), the country as a whole, and the eastern and western portions of the boreal forest region in Ontario, respectively. Therefore, they usually yielded average, general, low-risk misestimates of biomass instead of precise estimates. The biomass equations for such large spatial scales should be used with caution at very small scales, where local equations may be more appropriate (Jenkins et al. 2003; Lambert et al. 2005).

Application of Biomass Equations

As described above, the estimates of biomass equations were more consistent for medium-sized trees than for small and large trees, so biomass equations were generally more reliable for estimating forest biomass of medium sized wood.

More precautions should be taken against potential bias or errors of biomass equations for small and large trees, especially the latter, because of large variations in biomass estimates for these tree sizes and the greater possibility of bias and error. For example, the standard deviations of estimates of individual tree biomass for different equations increased as tree dimensions (DBH and height) increased. In other words, the larger the tree, the greater the uncertainties in the biomass estimates. This situation arose because most of the equations were developed with sample data sets dominated by medium-sized trees. This result corresponds with those of previous studies, which concluded that biomass equations applicable to merchantable trees may not be appropriate for small and large trees (Ouellet 1983; Penner et al. 1997). For small trees, in spite of the greater CV% of the estimates, several different equations could be applied at the same time to roughly define a scope of biomass without large bias and errors. In contrast, when calculating biomass for a forest formed by extremely large dominant and codominant trees, equations should be selected carefully, because the results estimated by different equations may be very different. For instance, Schroeder et al. (1997) pointed out that natural variation increases when many large-diameter trees are included, and a larger sample size might improve the regression relation. However, because of the variability inherent in large trees, it may not be feasible to reduce this level of error, even with an extremely large sample size (Schroeder et al. 1997). Jenkins et al. (2003) recommended that an effort be made to sample trees across the entire diameter range of a species, because current biomass equations usually lack estimates at large diameters (especially for hardwood species). As a result, before empirical equations are used to estimate the biomass of a stand dominated by large trees (e.g., ≥ 40 cm DBH), the equations should be validated with local data or an independent data set. In addition, greater precision of dimensions (i.e., DBH and height), particularly the former, is required when sampling large trees, because the biomass equations are usually more sensitive to exponential increases in DBH, and small errors in DBH measurement may lead to large bias in the biomass estimates for large trees.

There were no statistically significant differences in results obtained with two different methods (mean tree method and normal distribution approach) for converting individual tree biomass into stand biomass. Therefore, the mean tree method is recommended because of its simplicity. For the biomass of shrub (or tree sapling) understory, there were no apparent differences among the various equations. However, users should take into account that the understory cover is strongly correlated with transmitted light. With increased canopy density, a reduction of understory cover has been observed in comparisons of uncut shelterwood and clearcut stands (Lieffers 1993; Lieffers and Stadt 1994; Greenway and Lieffers 1997). Good estimation of aboveground biomass was a prerequisite for precisely estimating belowground biomass, because the latter is usually derived from the former.

CONCLUSIONS AND RECOMMENDATIONS

Numerous biomass equations have been reported for estimating forest biomass for a given species under various conditions. However, many of these equations have been presented inconsistently in terms of their form and regression parameters, and this inconsistency has complicated their application. This report has reviewed the methods of biomass measurement and estimation and has designed an approach for evaluating the existing biomass equations with the lowest bias for biomass estimates over a large spatial area, the west-central boreal forest of Canada. The evaluation approach entails (1) collection of existing biomass equations from sampling sites that are within or similar to the target study area, (2) establishment of a standard test data set representing average boreal forest growth of major species at a large spatial scale in west-central Canada, and (3) evaluation and identification of the biomass equations at a certain confidence level (i.e., ±10% for the means of biomass estimates). This approach is recommended for evaluating an average low-bias equation for a large spatial area, since it is less expensive and less time consuming to implement than traditional methods (which usually involve collection of empirical data across the entire large spatial unit and re-estimation of the parameter values on the basis of the new data).

In this study, 17 empirical biomass equations and two methods of extrapolating biomass from individual tree level to stand scale (commonly been used in Canada and/or the northern United States) were compared. The empirical biomass equations usually yielded more consistent and reliable estimates for medium-sized trees than for small and large trees. For west-central Canada, the equations developed for the Prairie provinces and/or a Canadian national system (i.e., formulas 3, 5, and 7) were better for estimating the individual tree biomass of six boreal forest species. For stand biomass, there were no significant differences between the mean tree and normal distribution techniques for extrapolating from individual tree biomass to the stand scale. The mean tree method is recommended because of its simplicity. For understory biomass, there were no significant differences among the equations for different tree saplings (or shrubs). For belowground biomass, the equations based on aboveground biomass are recommended.

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APPENDIX

Glossary

Biomass: The oven-dry weight (t/ha) of various biological components of a forestry ecosystem or an individual tree (Gray and Power 1997; Penner et al. 1997). One often-used definition of forest biomass is "the total quantity, at a given time, of living organisms of one or more species per unit area or of all the species in a community" (Johansson 1999). The biomass components defined in this study are shown in Figure A1.

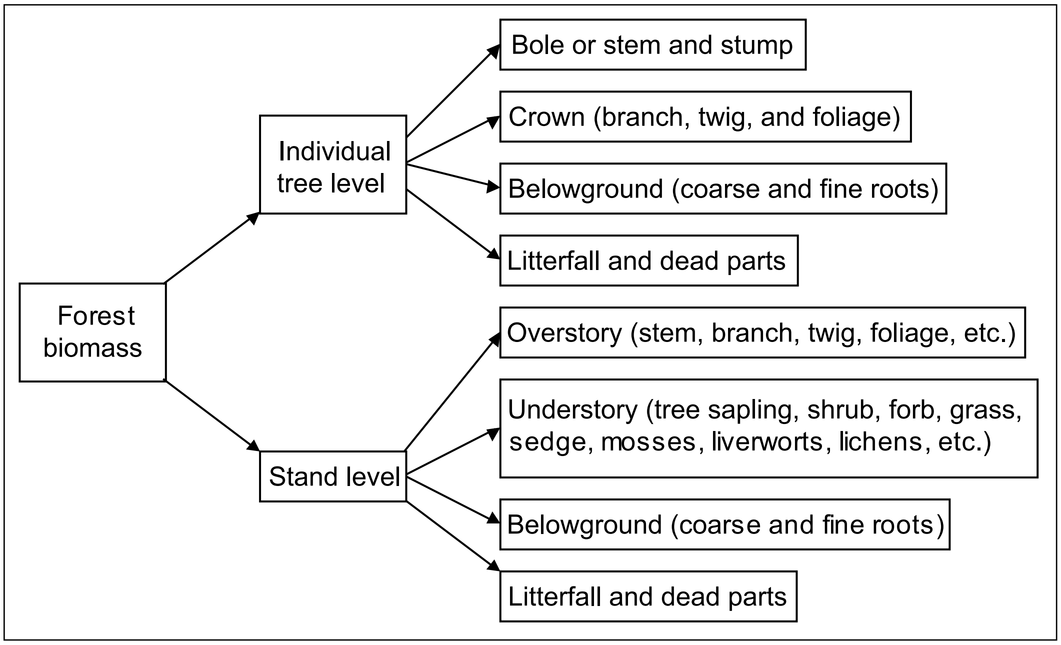

Figure A1. Schematic of forest biomass components defined in this study.

Diameter at breast height (DBH): Usually refers to diameter at breast height outside bark (DOB). Conventionally measured at a point approximately 4.5 ft (1.3 m ± 6.5 cm) above ground.

Tree height: Total height (m) of a tree from the point of germination to the tip of the tree, obtained with a clinometer (percent scale) and a metric surveyor's tape (usually a 30-m cloth tape).

Stand: Community of trees possessing sufficient uniformity in composition, age, arrangement, or condition to be distinguishable from the forest or other growth on adjoining areas, thus forming a management entity.

Even-aged stand: A stand with relatively small age differences (usually less than 20% variance) between individual trees.

Site index (SI): An expression of forest quality based on the height (ft) at a specific age (reference age 25, 50, or 70 years) of dominant and codominant trees in a stand. In this report, it refers to stand tree height at 50 years, according to the Canada's Forest Inventory 1991 (Penner et al. 1997).

Merchantable: Tree or stand that has attained sufficient size, quality, or volume to make it suitable for harvesting. "Submerchantable" means small trees, below a set DBH limit. "Unmerchantable" refers to the noncommercial parts of the stem (e.g., bark, stump, top).

Productivity class I forest land: Land that is incapable of producing a merchantable stand within a reasonable length of time.

Productivity class II forest land: Land that is capable of producing a merchantable stand within a reasonable length of time.

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