

forest management

Analyzing the Uncertainties in Use of Forest-Derived Biomass Equations for Open-Grown Trees in Agricultural Land

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Quantifying carbon in agroforestry trees requires biomass equations that capture the growth differences (e.g., tree specific gravity and architecture) created in the more open canopies of agroforestry plantings compared with those generally encountered in forests. Whereas forest-derived equations are available, equations for open-grown trees are not. Data from destructively sampled open-grown trees in the Northern Great Plains were used to examine the uncertainties in the use of forest-derived equations for open-grown trees. Three species, representative of major morphological types of agroforestry trees, were studied: green ash, Austrian pine, and eastern redcedar. Forest-derived equations provided good estimates of trunk biomass at lower diameter ranges but, as diameter increased, resulted in overestimation up to 40% for individual trees. Across the full diameter ranges, individual tree branch biomass was underestimated by 29–82%, depending on species and equation source (regional or nonregional). Although open-grown trunk and branch biomass curves diverged down and up, respectively, from their forest-derived counterparts, those for the whole tree tended to converge, albeit significantly above the forest-derived curves. Whole-tree biomass for individual trees was underestimated by at least 18%. To correct the biases, we studied the adjustment factor of forest- to open-grown tree biomass. It shows a power function with diameter. On a whole-tree basis, it was evaluated as a constant (1.2) independent of species and diameters. Application of this constant factor adjusted the biomass underestimation of three-species-mixed plantation by forest-derived equations from 21 to 4.6%, providing a cost-efficient approach to use forest-derived equations for open-grown trees in agriculture land.

Keywords: agroforestry, Austrian pine, carbon sequestration, eastern redcedar, green ash, windbreak

Agroforestry, the intentional integration of agriculture and forestry, is now one of several carbon (C) sequestering options being promoted for use in agricultural lands in the United States (Morgan et al. 2010, Council for Agricultural Science and Technology 2011). Much of agroforestry's appeal as a C sequestering tool is due to its high rate of C sequestration per unit area while occupying only a small fraction of the agricultural

enterprise and providing other benefits in support of agricultural production and stewardship (Nair et al. 2009, Schoeneberger 2009). Despite mounting information on C stocks in agroforestry systems, our capability to easily and accurately account for the contribution of agroforestry to C storage issues remains limited (Council for Agricultural Science and Technology 2011, Nair 2011).

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; kilograms (kg): 1 kg = 2.2 lb; hectares (ha): 1 ha = 2.47 ac.

Agroforestry influences the agricultural C cycle in many ways, both directly and indirectly (see Brandle et al. 1992, Schoeneberger 2009). Accounting to date has, however, focused predominantly on the wood components and largely on the aboveground woody biomass in the trunk and branches. Although this is not a complete C accounting, it does represent the major portion of woody biomass (Tufekcioglu et al. 2003, Peichl et al. 2006) as new C added to the system, as well as the more easily and accurately estimated and verified component (Schoeneberger 2009). Whether the task is to predict the impacts of agroforestry trees under hypothesized climate change scenarios or to report C credits for natural resource research and management, accurate biomass equations are essential to reliably estimate the C in this component of agroforestry systems.

Such agroforestry-specific equations are currently very limited (Kort and Turnock 1999, Nair 2011, Czerepowicz et al. 2012). Because agroforestry is not explicitly included in any national natural resource inventory (i.e., Forest Inventory Analysis Program [FIA] or the Natural Resources Inventory) (Perry et al. 2005, 2009), we lack the regional and US-wide data sets required for developing agroforestry-specific calculations that go into making C estimates. The expense of developing agroforestry-specific equations and the need for doing this in a timely manner prompted us to investigate alternative approaches, in this case the use of existing forest-derived biomass equations (i.e., developed using data from forest stands), for making more accurate C sequestration estimations for the open-grown trees that occupy agricultural land.

Forest-derived equations are available for many of the tree species generally used in agroecosystems (Ter-Mikaelian and Korzukhin 1997). Typically forest stands in forest regions develop under more closed-canopy coverage than tree plantings in agricultural landscapes and have minimal edge effects and more understory diversity that naturally evolved to fully use site resources (Perry et al. 2008). Most tree plantings in agricultural landscapes have only a few species and are planted with uniform spacing and in relatively narrow or small-patch configurations. This creates, in essence, an “edge” forest with the trees growing in a relatively open-canopy environment and experiencing significant edge effects, such as higher levels of radiation, direct wind momentum load, and agriculture residuals (i.e., fertilizers and pesticides). Under these conditions, competition for light, water, and nutrients among individual trees should also be less than that encountered under more closed-canopy conditions in forests. Because the physiognomy within a tree species is influenced by the degree and type of edge effects and competition for resources (Archibald and Bond 2003, Grote 2003), differences between forest- and open-grown trees in architecture (as described by trunk taper, external crown geometry, and internal structure) and in wood and bark specific gravities (oven-dry weight per unit green volume) should be expected.

Open-grown trees have larger crowns (Cole and Jensen 1982) and sharper trunk tapers (Sharma and Parton 2009) than more closed-canopy counterparts. The larger crown of open-grown trees is empirically expected to contribute more branch biomass. This tree architectural characteristic causes redistribution of biomass among tree parts and changes in tree specific gravity (Enquist and Niklas 2001). Zhou et al. (2011) demonstrated that trunk-specific gravity values for open-grown trees were greater than those published for forest-grown counterparts within the same geographic region. No significant difference in branch specific gravity was found. These findings infer that using a forest-derived equation could potentially either underestimate (due to greater specific gravity) or overestimate

(due to sharper trunk taper) trunk biomass. The degree of differences for these two attributes between open- and forest-grown trees, especially for individual species, then determines the amount of underestimation and/or overestimation or whether the underestimation caused by greater specific gravity balances out the overestimation caused by sharper trunk taper.

Because the parameters in a biomass equation [e.g., $M(D, h) = aD^b h^c + \varepsilon$ where M is biomass, D is dbh (e.g., 1.37 m), h is height; a , b , and c are parameters and ε is random error] are dependent on tree architecture and specific gravity (Ketterings et al. 2001), the accuracy of forest-derived equations for open-grown trees is uncertain (McHale et al. 2009). In this study, we analyze the uncertainties by comparing destructively sampled data for representative open-grown species with those predicted by various forest-derived equations. We determine how suitable these existing forest-derived equations are for estimating open-grown tree biomass and accordingly develop an adjustment method for possible use with the already available forest-derived equations as a cost-efficient means to more accurately estimate aboveground C storage in open-grown trees in agricultural landscapes.

Materials and Methods

Tree Species

Three tree species were selected for use in this study: green ash (*Fraxinus pennsylvanica* Marsh.), Austrian pine (*Pinus nigra* Arnold), and eastern redcedar (*Juniperus virginiana* L.). These species were selected based on their extensive use in agricultural settings, especially in agroforestry plantings; in addition, each represents a distinctive morphological type based on foliage shape: broad-leaf, needle, or scalelike foliage. The individual trees selected for use in this study were growing in single- or two-row shelterbelts or in the external rows of multiple-row shelterbelts.

Tree Portions

As defined by the US Department of Agriculture (USDA) Forest Service FIA, tree biomass is the total oven-dry weight of aboveground wood and bark components in a tree with diameter of ≥ 2.5 cm (Hansen 2001, Woodall et al. 2011). In FIA, a forest-derived equation for an individual tree in a dbh range of 2.5 to 12.6 cm is a weight-measured equation for whole-tree and for an individual tree of dbh ≥ 12.7 cm is a volume-converted equation for each of three portions: stump, the main stem segment from the ground surface to a height of 30.5 cm; bole, the main stem segment above the stump to the height where the diameter-outside-the-bark (DOB) is 10.2 cm; and top (above the bole) and limbs. For our analyses, the stump and bole, including their wood and bark, are referred to as the trunk and the remaining portions, excluding foliage, as the branches. For this study, we investigated the trunk and branch portions individually, and together, referred to hereafter as a whole-tree (i.e., aboveground wood and bark components). When the use of FIA forest-derived equations is analyzed, an open-grown equation for an individual tree in a dbh range of 2.5 to 12.6 cm is for whole-tree and for an individual tree of dbh ≥ 12.7 cm is for each of two portions: trunk and branches. When the use of other forest-derived equations is analyzed, open-grown equations are developed accordingly.

Sources of Forest-Derived Equations

The biometric relationship of biomass to diameter and/or height in trees varies not only among species but also geographically within a species due to variability in soil and climate (Jenkins et al. 2003).

Table 1. Descriptive summary of tree samples (dbh of 1.37 m).

Species	Number of sampled trees						Total	Age (yr)	dbh (cm)	Height (m)
	Volume-measured year		Weight-measured year							
	1996	1997	1990	2001	2002	2004				
Green ash	6	12	3	7	9	3	40	15–54	5.9–41.6	4.1–16.8
Austrian pine	8	9	0	2	6	3	28	10–41	3.5–38.4	2.6–14.7
Eastern redcedar	6	9	3	2	10	3	33	6–63	2.6–30.7	2.1–13.5

Regional forest-derived equations (regional equations) are available from FIA (Hansen 2001) and technically are the first choice for estimating open-grown tree biomass when open-grown equations are not available. If regional equations are unavailable, two other alternatives are forest-derived equations outside the region (nonregional equation) (Tritton and Hornbeck 1982) and self-fitted forest-derived equations (self-fitted equation) using data generated by various published nonregional equations (Pastor et al. 1984). All three alternatives (regional, nonregional, and self-fitted equations) were used to examine the uncertainties in estimating open-grown tree biomass and to develop an adjustment technique for use with forest-derived equations to improve the accuracy of biomass estimates in open-grown trees.

Analysis Methods

A biomass estimate for an area at any given scale is generated by measuring individual trees within plots and then substituting diameter and/or height values of measured trees into equations. The accuracy of each of the forest-derived equations for open-grown trees over a diameter range can be statistically analyzed against true biomass values acquired from destructively sampled individual open-grown trees. However, the accuracy of a biomass equation varies as diameter and/or height values vary, as does a statistical equation at different values of its independent variables (Bates and Watts 2007). Therefore, the trees of each species for destructive measurements were sampled at a diameter increment as equal as possible in a uniform distribution to cover the diameter range of the species.

It is unlikely that the trees for any species in a plot will have the same uniform distribution of diameter sizes as the trees destructively sampled. Likewise, all species together within a measurement plot may not have the same diameter distribution as that of a single species. In such a case, the accuracy of biomass estimates using forest-derived equations for individual open-grown trees may not fully represent the accuracy in total biomass for each species or for all coexisting species in a plot. Accordingly, the uncertainties in the use of forest-derived equations need to be analyzed further for individual species and for all coexisting species in a plot.

For individual open-grown trees, the uncertainties were analyzed by comparing the values estimated using a forest-derived equation with the true biomass values destructively measured in the field. For an individual species in a plot, both the open-grown equations developed using the data from open-grown trees and the forest-derived equations acquired from literature sources were used to estimate the biomass in a plot. The sum of biomass estimates from individual species is the biomass of all coexisting species in the plot. The biomass values averaged over all measured plots by equation type were then compared for analyses.

Model Forms of Equations

Statistical equations with the same independent variables can generate different estimates at the same values of independent variables. This may be due to inconsistencies in model forms between equations and/or inequalities in corresponding parameters. By using the same model form, any difference between estimates from different equations used in this study can be ascribed to the inequalities in corresponding parameters depending on tree specific gravity and architecture (Ketterings et al. 2001). We, therefore, purposely used the model form of each of the three types of forest-derived equations to develop the corresponding open-grown equations.

Approaches

The uncertainties in the use of regional, nonregional, and self-fitted forest-derived equations for open-grown trees were analyzed by comparing (1) individual tree biomass values estimated by forest-derived equations with true biomass values from destructively sampled trees, (2) individual species biomass values estimated by forest-derived equations with those estimated by open-grown equations, and (3) three-species-combined plantation biomass values as estimated in (2).

Data Collection

Study Region and Field Sampling

With the assistance of USDA Natural Resource Conservation Service personnel, 33 shelterbelts with one or more of the three study species were identified within 14 Great Plains counties in two states: Nebraska (Cass, Dawson, Johnson, Lancaster, McPherson, Morrill, and Saunders) and Montana (Chouteau, Dawson, Liberty, Ponderosa, Richland, Roosevelt, and Sheridan). During the dormant seasons in 2001, 2002, and 2004, a representative segment in each shelterbelt was selected and sampled. Each segment included ≥ 30 trees for each study species and was designated a measurement plot. Within the plot, the dbh (1.37 m) and height of each tree were measured. Based on these measurements, an average single-stem tree (mean diameter ± 1 cm and mean height ± 0.5 m) with representative crown architecture from each species was selected and destructively measured. Where it was permitted, one or two additional trees from each species, representing smaller and/or larger individuals, were further sampled and destructively measured (Table 1). The procedures of harvesting the sampled trees and measuring their trunk and branch weight (weight-measured biomass) in the field and laboratory were documented in Zhou et al. (2011).

Additional data collected in 1990, 1996, and 1997 at the University of Nebraska Agricultural Research and Development Center, Mead, Nebraska, USA, were also included in the analyses (Table 1). The 1990 data were the weight-measured biomass collected in a fashion similar to that for the measurements after 2000. The 1996

Table 2. Specific gravities (based on oven-dried weight and green volume) used for conversion of wood and bark volumes into biomass.

Species	Trunk			Branches		
	Wood	Bark	Source	Wood	Bark	Source
Green ash	0.563	0.456	Manwiller (1979), Schlaegel (1984), Clark et al. (1985)	0.548	0.458	Manwiller (1979), Clark et al. (1985)
Austrian pine	0.427	0.240	Wahlgren et al. (1968), Smith (1985)	0.333	0.268	Erickson (1972)
Eastern redcedar	0.480	0.400	Simpson and TenWolde (1999)	0.440 ^a	0.400 ^a	Smith (1985), Denig (1997)

^a The specific gravities (g cm^{-3}) specified for eastern redcedar branches could not be found. Values for trunk were found in Smith (1985), Denig (1997), Simpson and TenWolde (1999), and Gilman and Watson (2003). The smallest trunk wood specific gravity of 0.440 g cm^{-3} from Smith (1985) and Denig (1997) and the smallest bark specific gravity of 0.400 g cm^{-3} from Smith (1985) were used.

and 1997 data sets were measured as part of a study on tree aerodynamic structure and had volume data available that could be converted to biomass (volume-converted biomass).

Because biomass measurements are labor-intensive and time-consuming, converting tree volume into biomass is an adopted/standard approach in the development of forest equations. On the other hand, long-term volume data are available and have been standardized in the wood industry with a long history for forest inventory. FIA has pursued this approach since the 1980s (Smith 1985, Hansen 2001) and continues to use this approach (Woodall et al. 2011). To minimize the uncertainties and increase accuracy in our study, we considered additional technical details (e.g., use of branch-specific gravities, bark fissure adjustment, and conversion verification against weight-measured biomass) in the conversion of volume to biomass as follows.

Conversion of Volume to Biomass

For volume measurements, each sampled, open-grown tree was cut near the ground surface, leaving no stump. By cutting limbs flush with the main stem, the tree was separated into two component groups: stem (trunk plus top) and limbs including foliage.

Trunk

For each stem, length was measured to the nearest centimeter and diameter to the nearest millimeter at heights of 0, 0.50, 1.0, 1.37, and 1.50 m and thereafter at heights of every 1-m increment upward until the proximal base of the most distal section was shorter than 1 m. For each measured height, a 3-cm-thick disk was marked on the north side, cut off just above the measured height from the stem and kept fresh for determinations of wood and bark volumes. Rings were counted for age determination at the working surface (the bottom side of disk) of the stem disk at the ground surface.

DOB on the working surface of each stem disk was measured to the nearest millimeter in the west-east and north-south directions. These diameters were averaged to represent DOB at the height of the disk working surface. Diameter-inside-the-bark (DIB) was similarly measured and determined. By using the values of DOB and DIB from all stem disks, the green volumes of wood and bark for the stem were calculated using the stem analysis algorithm for volume calculation in Husch et al. (2003). By excluding the green wood and bark volumes in the top, the green wood and bark volumes for stem were adjusted as for the trunk volumes. Because of the void volume of fissures in the bark, the bark volume was adjusted using a percentage of bark void volume of 17.7% for green ash (Choong and Cassens 1976), 26.0% for Austrian pine, and 28.0% for eastern redcedar (Krier and River 1968).

To convert the green volume of trunk to biomass, the conversion factors of wood and bark specific gravities are needed. These factors are available for green ash and eastern redcedar from a number of literature sources (Schlaegel 1984, Clark et al. 1985, Smith 1985)

but are unavailable for Austrian pine. For this species, we used the conversion factors, as well as site index and biomass equations, for a very similar species, red pine (*Pinus resinosa* Ait.) (Raile and Jakes 1982, Harlow et al. 1991).

Because specific gravities of wood and bark for each species vary geographically (Wiemann and Williamson 2002), as do biomass equations (Jenkins et al. 2003), FIA uses regionally measured specific gravities for biomass equations (Smith 1985). Zhou et al. (2011) found that regional specific gravity values from forest-grown trees tended to result in an underestimation of biomass for open-grown trees when used to calculate biomass from volume. Specific gravity values reported in the literature for wood and bark of each tree species were therefore tested using the methodology in Zhou et al. (2011). Our weight-measured trunk biomass values had corresponding volume values for wood and bark. After each volume value was converted into a biomass value using a specific gravity, there was a pair of biomass values (weight-measured and volume-converted) for each trunk component from each specific gravity. The specific gravity producing the smallest difference in summation between the pair of biomass values within a species (Table 2) was used to convert trunk volume to biomass.

Branches

Foliage on limbs, if any, was picked flush with each limb. The compound limbs were separated into individual limbs, each of which is a primary one with a bud and a joint to another limb or trunk. By measuring the length (l) to the nearest millimeter and middle diameter (d) to the nearest 0.1 mm using a digital caliper, limb volume (V) was calculated using

$$V = f\pi l(d/2)^2 \quad (1)$$

where f is the limb-volume adjustment factor (i.e., volume ratio of a limb to a cylinder having the same middle diameter and length as the limb).

A limb-volume adjustment factor for each species was estimated from a number of limbs (345 for green ash, 216 for Austrian pine, and 303 for eastern redcedar) across the range of sizes using accurate volume measurements as outlined in Zhou et al. (2002). The limb-volume adjustment factors for green ash had different means and SDs in two limb size classes (middle cross-sectional area \times length); however, they were independent of limb size within a class (1.049 ± 0.032 for limb size $\leq 0.1 \text{ dm}^3$ and 1.259 ± 0.039 for limb size $> 0.1 \text{ dm}^3$). For the other two species, the factor was independent of the limb size (0.926 ± 0.022 for Austrian pine and 1.154 ± 0.026 for eastern redcedar).

The summation of green volumes for individual limbs is a green volume for the limb component. Because this volume includes wood and bark, which have different specific gravities, for conversion of volume into biomass, the green wood and bark volumes were

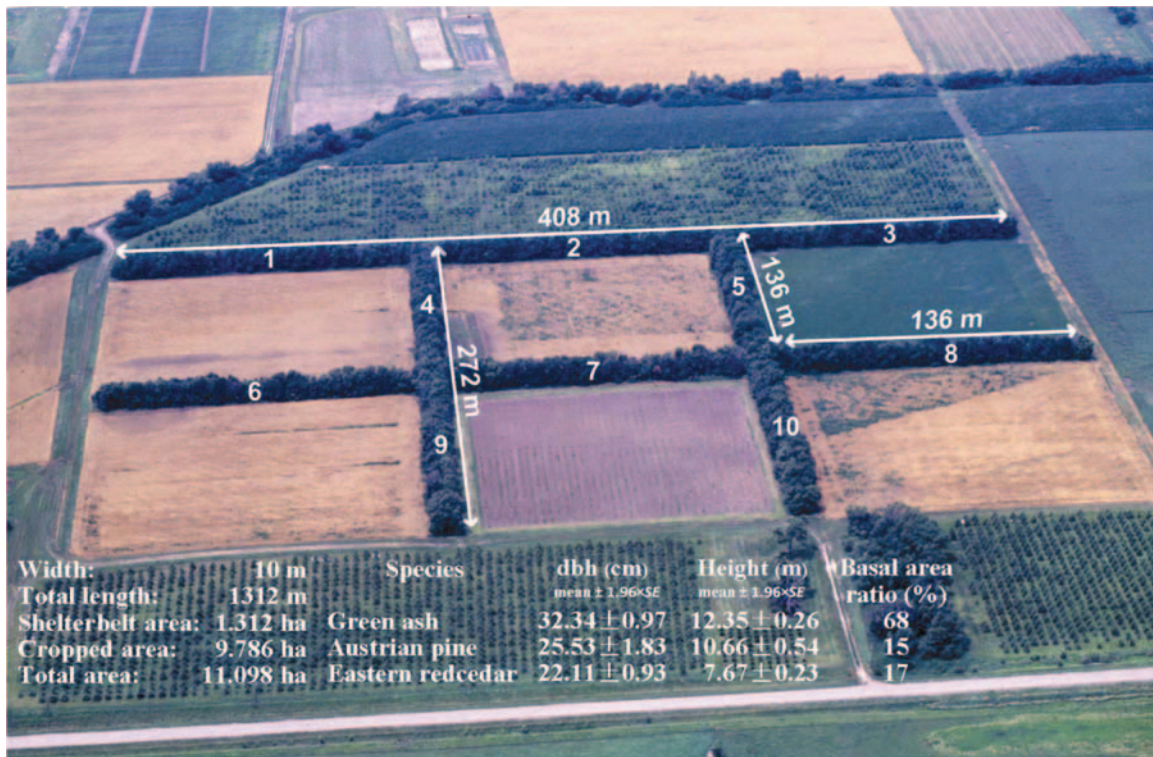


Figure 1. A 48-year-old, three-species-mixed shelterbelt network at the University of Nebraska Agricultural Research and Development Center near Mead, Nebraska, USA (dbh represents dbh of 1.37 m, SE is the SE of the sample mean, and mean ± 1.96 × SE represents the 95% confidence interval).

arithmetically separated using bark percentage (Smith 1985). By including the top green wood volume, the green wood volume for the limb component was adjusted for branches. By including the top green bark volume, the green bark volume for the limb component was adjusted for branches. The minimal fissures in branch bark were assumed not to generate a void volume great enough to cause a significant error in volume determination. Therefore, branch bark volume was not adjusted for fissures.

To convert the branch volumes into biomass, the branch specific gravities of wood and bark for open-grown trees are required. These specific gravity values are very limited in the literature for forest-grown trees and even rarer for open-grown trees. Fortunately, no significant difference in branch specific gravity was found between forest- and open-grown trees for the same species (Zhou et al. 2011). Values for forest-grown trees that were found in the literature (Table 2) were used in conversion of branch volumes to biomass.

Shelterbelt Network Description and Plot Measurements

A two-row, three-species shelterbelt network planted in 1965 and located at the University of Nebraska Agricultural Research and Development Center (41°29' N, 96°30' W, 354-m altitude, and Typic Argiudoll soil) was used to test the use of forest-derived equations for individual species and for a three-species-combined shelterbelt network (Figure 1; hereafter referred to as shelterbelt network). One row consisted of alternating green ash and eastern redcedar and the other consisted of alternating pairs of green ash and Austrian pine. Spacing was 2 m within a row and 4 m between rows.

In each of the five shelterbelt segments (1, 3, 5, 7, and 9 in Figure 1), one 100-m long plot was measured for dbh, height, and crown dimensions in 1990 and remeasured in 1996, 1997, 2004, and 2011. All data from different years were used to define the relation-

ship of height to dbh in the analyses, and 2011 data were used to estimate biomass of trees in the shelterbelt network using forest-derived and open-grown equations.

Results

Use of the Regional Forest-Derived Equations

According to the FIA-defined regions (Hansen 2001), the equations specified for the North Central Region are technically considered the regional forest-derived equations (regional equations) for our study sites. Used by the FIA, these equations are an amalgamation of equations for the gross bole volume, stump wood volume, top and limb biomass, and small tree (diameter of <12.7 cm) biomass, with conversion factors including wood and bark specific gravities and bark percentages (Smith 1985, Hahn and Hansen 1991).

We summarized the amalgamation for trunk, branches, and whole-tree as three biomass models of $M_{ij}(D, S)$ in kg, where D is dbh in cm and S is site index in ft as determined by the dominant height and age of trees (Carmean et al. 1989); subscript i can be R , N , S , F , or O for an equation type: regional, nonregional, self-fitted, forest-derived (i.e., all forest-derived in general), or open-grown equation; and j can be T , B , or W for a tree portion: trunk, branches, or whole-tree. Subscripts i and j are used for other functions, variables, and parameters throughout this study and have the same indication.

Trunk

$$M_{RT}(D, S) = a_{RT1}S^{a_{RT2}}[1 - \exp(a_{RT3}D^{a_{RT4}})] + a_{RT5}D^2 + \varepsilon_{RT}$$

$$D \geq 12.7 \quad (2)$$

Table 3. Parameters in regional forest-derived biomass and open-grown biomass equations.

Parameter	Green ash		Austrian pine		Eastern redcedar	
	Regional forest-derived ($i = R$)	Open-grown ($i = O$) $a_{Ojk} \pm SE(a_{Ojk})$	Regional forest-derived ($i = R$)	Open-grown ($i = O$) $a_{Ojk} \pm SE(a_{Ojk})$	Regional forest-derived ($i = R$)	Open-grown ($i = O$) $a_{Ojk} \pm SE(a_{Ojk})$
Trunk ($j = T$)						
a_{iT1}	1,240.8	1,304.3 ± 419.0	1,558.8	1,590.6 ± 255.5	1,555.8	1,624.4 ± 475.8
a_{iT2}	0.2283	0.2301 ± 0.0154	0.4148	0.4199 ± 0.0359	0.1250	0.1352 ± 0.0095
$a_{iT3} (\times 10^{-6})$	-5.9401	-18.186 ± 8.764	-1.8919	-7.2008 ± 2.3164	-9.1952	-58.231 ± 20.468
a_{iT4}	2.800	2.3899 ± 0.1365	2.724	2.3374 ± 0.2104	2.626	1.9367 ± 0.1406
$a_{iT5} (\times 10^{-2})$	2.2772	2.4364 ± 0.7541	1.4122	1.4708 ± 0.2742	1.9014	2.0579 ± 0.4775
Residual error		29.597		27.686		8.3650
SE range ^a		29.416–33.592		28.166–31.503		8.5980–9.7865
df		27		17		20
Branches ($j = B$)						
a_{iB1}	0	1.0167 ± 0.0444	0.092	0.5943 ± 0.0333	0.061	1.5392 ± 0.1620
a_{iB2}	-0.4710	-11.0952 ± 3.5899	-1.628	-11.7662 ± 2.723	-0.659	-2.1115 ± 0.7424
Residual error		46.370		25.563		18.323
SE range		44.009–47.927		25.581–27.806		18.761–20.956
df		25		15		18
Whole-tree ($j = W$)						
a_{iW}	2.4324	2.5027 ± 0.3285	2.4324	3.3033 ± 0.5509	2.4324	2.7675 ± 0.3243
Residual error		43.518		32.840		22.571
SE $D < 12.7$		5.6763–6.0006		4.6769–5.2489		4.3561–4.9252
Range $D \geq 12.7$		50.936–56.318		37.024–40.922		19.770–22.159
df		32		20		25
Diameter range		5.9–41.6		3.5–38.4		1.2–30.7

Regional forest-derived ($i = R$) biomass and open-grown ($i = O$) biomass equations are based on models 2–7, where biomass is in kg, diameter at height of 1.37 m (D) is in cm, and site index is in ft [df is degrees of freedom and $SE(a_{Ojk})$ is the SE of parameter a_{Ojk}].

^a As indicated by model 7, the standard error (SE) for an individual prediction depends on the diameter and site index of the predicted tree; therefore, a SE range is given for each species.

where a_{RTk} ($k = 1, 2, \dots, 5$) is a parameter and its subscript k indicates the sequential number of this parameter in a model and ϵ_{RT} indicates random error.

Branches

$$M_{RB}(D, S) = a_{RT1} S^{a_{RT2}} [1 - \exp(a_{RT3} D^{a_{RT4}})] \left[a_{RB1} + \left(\frac{D}{2.54} \right)^{a_{RB2}} \right] + \epsilon_{RB} \quad D \geq 12.7 \quad (3)$$

Whole-tree

$$M_{RW}(D, S) = \begin{cases} M_{RT}(D, S) + M_{RB}(D, S) & D \geq 12.7 \\ \left(\frac{D}{12.7} \right)^{a_{RW}} [M_{RT}(12.7, S) + M_{RB}(12.7, S)] + \epsilon_{RW} & 2.5 \leq D < 12.7 \end{cases} \quad (4)$$

Parameter values in models 2–4 for the regional equations of the three species are listed in Table 3. By using our data from destructively sampled open-grown trees and the Gauss-Newton or Marquardt method in the SAS NLIN procedure, these parameters (a_{Rjk}) in models 2 to 4 were estimated as a_{Ojk} for open-grown equations [$M_{Oj}(D, S)$] and are listed in Table 3. The coefficients of determination (R^2) for the open-grown equation are ≥ 0.93 for trunk, ≥ 0.86 for branches, and ≥ 0.95 for whole-tree (Figure 2).

Given the residual error of regression [$RE(\hat{M}_{Oj})$, where \hat{M}_{Oj} is a predicted biomass value using the open-grown equation] as

$$RE(\hat{M}_{Oj}) = \sqrt{\frac{\mathbf{r}'_{Oj} \mathbf{r}_{Oj}}{n - p_{Oj}}} \quad (5)$$

where \mathbf{r}_{Oj} is a residual vector, [$M_{Oj1} - \hat{M}_{Oj1}, \dots, M_{Ojn} - \hat{M}_{Ojn}$][']; n is the number of samples; p_{Oj} is the number of parameters in the model; and the denominator of $n - p_{Oj}$ is the degree of freedom for the error and also given the Jacobian matrix ($J_{Oj \ n \times \ p}$ with elements of $\partial M_{Oj} / \partial a_{Ojk}$, a partial derivative of the model with respect to a parameter), the SE of parameter [$SE(a_{Ojk})$] is expressed as

$$SE(a_{Ojk}) = \sqrt{(J'_{Oj \ n \times \ p} J_{Oj \ n \times \ p})^{-1}(k, k) RE^2(\hat{M}_{Oj})} \quad (6)$$

(SAS Institute, Inc. 1999, Bates and Watts 2007) and the standard error of an individual prediction by an open-grown equation is expressed as

$$SE[\hat{M}_{Oj}(a_{Oj1}, \dots, a_{Ojp}, D_0, S_0)] = \sqrt{[J_{Oj1 \times \ p}^0 (J'_{Oj \ n \times \ p} J_{Ojn \times \ p})^{-1} J_{Oj1 \times \ p}^0 + 1] RE^2(\hat{M}_{Oj})} \quad (7)$$

where D_0 , S_0 , and $J_{Oj1 \times \ p}^0$ are the dbh, site index, and Jacobian vector of the tree whose biomass value is predicted. For a predicted tree as indicated by superscript 0, this Jacobian vector now is a tree-specified vector that is a function of D_0 , S_0 , and estimated parameters; therefore, given the estimated parameters, the SE of the predicted biomass value varies with the independent variables of dbh and site index in the equation.

The regression residual error (model 5), SEs for individual parameters (model 6), and the range of SEs of individual prediction (model 7)

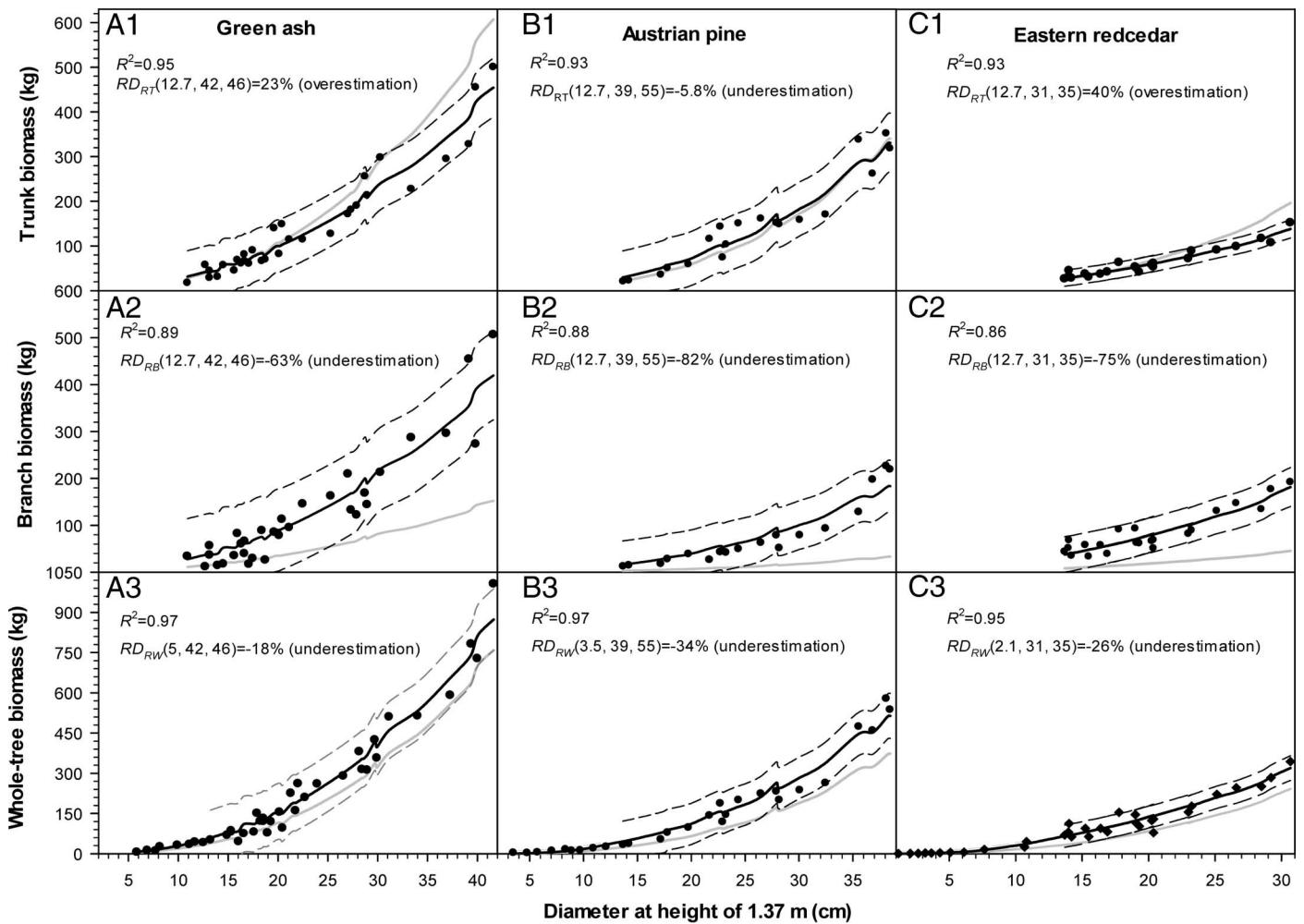


Figure 2. Comparisons of regional forest-derived biomass with open-grown biomass equations for estimating individual tree biomass. R^2 is the coefficient of determination, i.e., the proportion of variance explained by the equation; $RD_{R_j}(D_1, D_2, S)$ is defined by model 8, the relative difference between a regional forest-derived and an open-grown equation over a range of diameter from D_1 to D_2 at the site index of S where subscript j can be T , B , or W , representing trunk, branches, and whole-tree, respectively. The black solid line represents the open-grown equation, the gray solid line represents the regional forest-derived equation, the dashed line represents 95% CL of the open-grown equation for individual predicted values (see model 7, estimated using options of L95 and U95 for the OUTPUT statement in SAS Procedure NLIN [SAS Institute, Inc. 1999]), and dots represent destructively measured data.

are listed in Table 3. Based on model 7, the SE used for a 95% confidence limit (CL) of an individual prediction was calculated by the SAS NLIN procedure (SAS Institute, Inc. 1999).

Individual Open-Grown Trees

Data from destructively sampled individual open-grown trees along with their corresponding regional equation curves and open-grown equation curves with their 95% CL (the significant level of $P < 0.05$ is used throughout) for individual predicted values are plotted against diameter in Figure 2. Regional trunk equations were found to correctly estimate the trunk biomass of open-grown trees for all three species at lower diameter ranges (<20 cm for green ash, <39 cm for Austrian pine, and <18 cm for eastern redcedar), but tended to overestimate trunk biomass as diameter increased beyond the ranges. Regional equations significantly underestimated branch biomass throughout the diameter range. The overestimation by the regional trunk equation could not offset the underestimation from the regional branch equation within the corresponding range. As a result, aboveground woody biomass values on a whole-tree basis for all three species were underestimated throughout the diameter ranges.

The degree of underestimation (or overestimation) over a diam-

eter range of D_1 to D_2 can be assessed using the relative difference in biomass estimations [$RD_{ij}(D_1, D_2, S)$] between forest-derived and open-grown equations and is calculated by

$$RD_{ij}(D_1, D_2, S) = \frac{100}{(D_2 - D_1)} \int_{D_1}^{D_2} \frac{M_{ij}(D, S) - M_{oj}(D, S)}{\int_{D_1}^{D_2} M_{oj}(D, S) dD} dD \quad (8)$$

where the value of “100” converts the relative difference to a percentage. For given values of D and S , the relative difference is described by $[M_{ij}(D, S) - M_{oj}(D, S)]/M_{oj}(D, S)$. Therefore, a term of $M_{oj}(D, S)/\int_{D_1}^{D_2} M_{oj}(D, S) dD$ is used to arithmetically weight the relative difference, resulting in the term inside the outermost integration in model 8. A positive relative difference reflects overestimation, and a negative relative difference reflects underestimation from use of the forest-derived equation, where the absolute value represents the magnitude of difference.

Using the composite trapezoidal rule for numerical integration and a diameter subinterval of 0.25 cm, the relative difference in

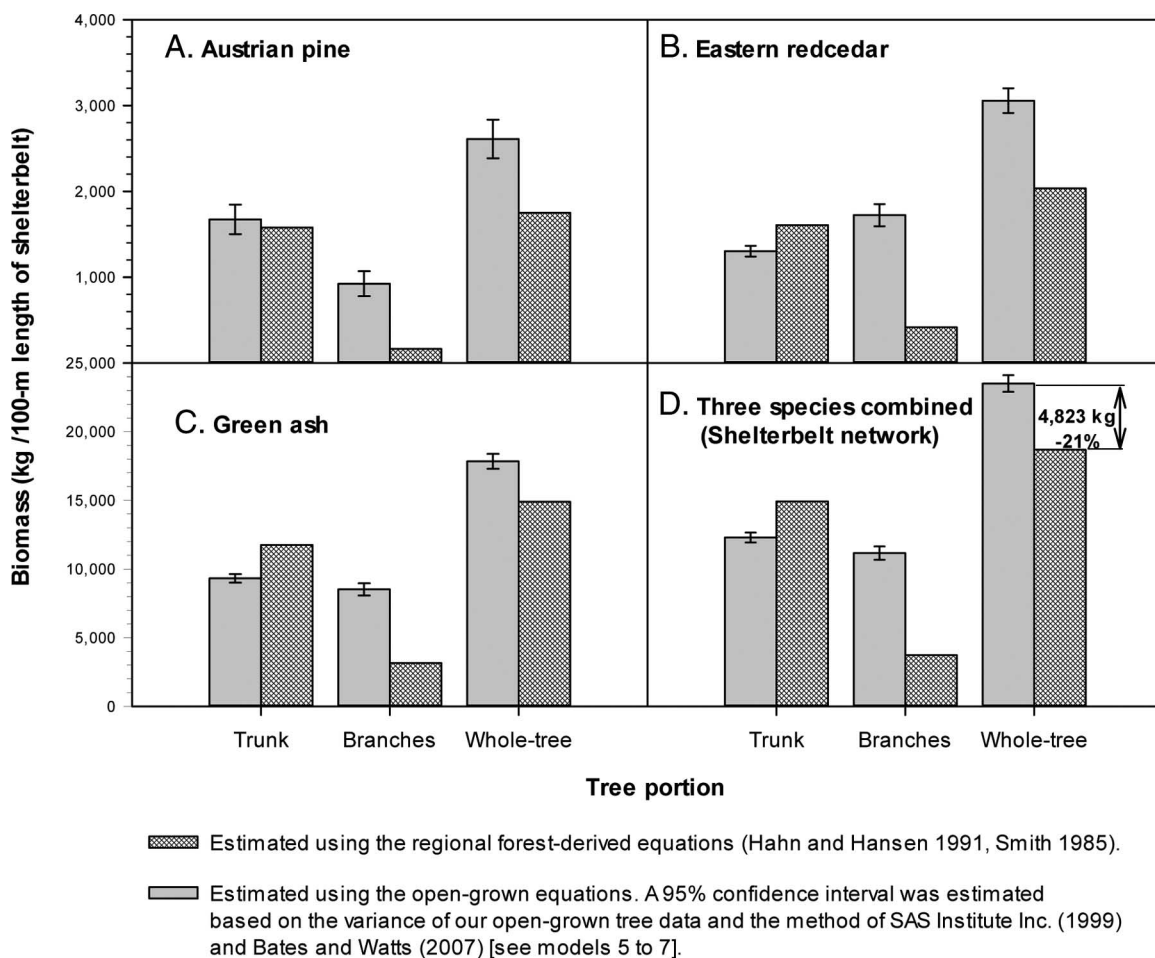


Figure 3. Comparison of regional forest-derived biomass with open-grown biomass equations for estimating the biomass of individual species and the three-species-combined shelterbelt network.

biomass estimation between regional and open-grown equations was calculated as defined by model 8 for trunk, branch, and whole-tree biomass in the three species for an average site index of our study sites (46 for green ash, 55 for Austrian pine, and 35 for eastern redcedar) (Figure 2). Within the diameter ranges of our sampled trees, the regional equations overestimated trunk biomass by 23% for green ash and by 40% for eastern redcedar, respectively, and underestimated trunk biomass by 5.8% for Austrian pine. Branch biomass was underestimated for the three study species by 63–82%. Combined, whole-tree biomass was underestimated for all three species by 18–34%.

Individual Species and the Shelterbelt Network

Trunk, branch, and whole-tree biomass values for five segments (1, 3, 5, 7, and 9) in the shelterbelt network (Figure 1) were estimated for each species in kg per 100-m length segment by submitting individual tree data measured in 2011 into the regional equations and open-grown equations, respectively. Biomass estimates for each tree portion by species and all species combined were averaged by equation type over the five segments to provide comparison values as shown in Figure 3 for individual species and the shelterbelt network.

In Figure 3A–C, it can be seen that the regional equations, although not significantly different, tended to underestimate trunk biomass for Austrian pine at the species level by 5.6%; however, trunk biomass was significantly overestimated for green ash by 26%

and for eastern redcedar by 23%. The underestimation for Austrian pine is much less than the overestimation for green ash and eastern redcedar. As a result, regional equations significantly overestimated the trunk biomass of the shelterbelt network by 21% (Figure 3D). In contrast, the branch biomass at the species level was significantly underestimated by the regional equations for all three species, individually from 63% for green ash (Figure 3C) to 82% for Austrian pine (Figure 3A) and for the shelterbelt network by 67% (Figure 3D).

For any species, the magnitude of trunk biomass overestimation by the regional equations did not offset its branch biomass underestimation, resulting in a significant underestimation of whole-tree biomass for each of individual species (Figure 3A–C). For the shelterbelt network, whole-tree biomass was significantly underestimated by 21% (4,823 kg/100-m length segment of shelterbelt) (Figure 3D).

Use of the Nonregional Forest-Derived Equations

A tree biomass equation is technically biased when used for trees outside the region for which it was developed. To analyze the uncertainties in use of nonregional forest-derived equations (nonregional equations), we first had to minimize the bias of estimates for trees in our study region. Three sets of nonregional equations for each species in the diameter ranges of our study trees were acquired from different literature sources. Each set of equations includes three equations for trunk, branches, and whole-tree, respectively.

Table 4. Nonregional forest-derived ($i = N$) biomass and open-grown ($i = O$) biomass equations.

Source	Tree portion j	Model $M_{ij}(D, h)^a$	Parameter							
			Nonregional forest-derived ($i = N$)			Open-grown ($i = O$)				
			$a_{Nj1} \times 10^{-2}$	a_{Nj2}	$a_{NW3}^3 a_{NW4} \times 10^{-2}$	$a_{Oj1} \pm SE(a_{Oj1}) \times 10^{-2}$	$a_{Oj2} \pm SE(a_{Oj2})$	$a_{OW3} \pm SE(a_{OW3}) / a_{OW4} \pm SE(a_{OW4}) \times 10^{-2}$	$RE(\hat{M}_{ij})$	
Green ash										
Alemdag (1984)	T	$a_{ij1}D^2h + a_{ij2} + \varepsilon_{ij}$	$12.7 \leq D \leq 40.2^b$	1.560	-6.100		1.867 ± 0.040	0		3.642
	B	$a_{ij1}D^2h + \varepsilon_{ij}$	$5.0 \leq D < 12.7$	0.3037	6.100	2.092	1.681 ± 0.081	0	NA	7.311
	W	$a_{iW3}D^2h + a_{iW4} + \varepsilon_{iW}$	$D < 5.0$	1.864	0	60.00	3.547 ± 0.094	0	NA	8.601
Schlaegel (1984)	T	$a_{ij1}D^{2ij2} + \varepsilon_{ij}$	$2.5 \leq D < 78.7$	13.48	2.263		7.487 ± 3.066	2.335 ± 0.116		4.579
	B			1.952	2.386		2.199 ± 0.671	2.657 ± 0.175		5.703
	W			15.47	2.280		8.491 ± 2.768	2.483 ± 0.092		6.616
Perala and Alban (1994)	T	$a_{ij1}D^{2ij2} + \varepsilon_{ij}$	$4.0 \leq D < 32.0$	11.79	2.211		Same as above for Schlaegel (1984)			
	B			1.396	2.585					
	W			11.00	2.373					
Austrian pine										
Ker (1980)	T	$a_{ij1}D^{2ij2} + \varepsilon_{ij}$	$2.3 \leq D < 33.6$	6.141	2.386		6.825 ± 2.003	2.325 ± 0.167		4.870
	B			0.8547	2.481		0.05758 ± 0.0225	3.513 ± 0.217		2.432
	W			7.001	2.399		3.316 ± 1.290	2.658 ± 0.136		5.513
Alemdag (1983)	T	$a_{ij1}D^2h + a_{ij2} + \varepsilon_{ij}$	$12.7 \leq D \leq 55.1$	1.430	-3.200		1.729 ± 0.043	0		3.843
	B	$a_{ij1}D^2h + \varepsilon_{ij}$	$5.0 \leq D < 12.7$	0.3508	3.200	1.771	0.9493 ± 0.0465	0	5.641 ± 0.859	4.190
	W	$a_{iW3}D^2h + a_{iW4} + \varepsilon_{iW}$	$D \leq 5.0$	1.781	0	25.00	2.686 ± 0.059	0	27.00 ± 4.12	5.338
Perala and Alban (1994)	T	$a_{ij1}D^{2ij2} + \varepsilon_{ij}$	$3.0 \leq D < 46.0$	2.956	2.569		Same as above for Ker (1980)			
	B			4.251	2.313					
	W			7.033	2.425					
Eastern redcedar										
Schnell (1976)	T	$a_{ij1}D^{2ij2} + \varepsilon_{ij}$	$12.7 \leq D < 50.8$	10.61	2.227		15.88 ± 4.14	1.971 ± 0.121		1.904
	B			2.403	2.466		19.66 ± 5.18	1.991 ± 0.189		3.919
	W			12.26	2.206		32.70 ± 4.65	2.007 ± 0.155		5.620
Alemdag (1983)	T	$a_{ij1}D^2h + a_{ij2} + \varepsilon_{ij}$	$12.7 \leq D \leq 37.5$	1.362	-2.800		1.476 ± 0.063	0		2.703
	B	$a_{ij1}D^2h + \varepsilon_{ij}$	$5 \leq D < 12.7$	1.111	2.800	1.771	1.937 ± 0.107	0	5.545 ± 0.592	4.616
	W	$a_{iW3}D^2h + a_{iW4} + \varepsilon_{iW}$	$D < 5.0$	2.473	0	25.00	3.399 ± 0.164	0	55.87 ± 3.32	7.064
Wittwer et al. (1999)	T	$a_{ij1}D^{2ij2} + \varepsilon_{ij}$	$12.7 \leq D \leq 37.5$	4.021	2.369		Same as above for Schnell (1976)			
	B			14.07	1.935					
	W			15.00	2.154					

Subscript j can be T , B , or W , representing a tree portion: trunk, branches, or whole-tree, respectively; $SE(a_{ijk})$, the SE of parameter a_{ijk} (see model 6); $RE(\hat{M}_{ij})$, residual error of regression for the open-grown equation (see model 5). NA, not available because the diameters of sampled open-grown trees for this species were not smaller than 5.0 cm. ^a $M_{ij}(D, h)$ in kg (D in cm, diameter at height of 1.37 m; h in m, height; ε_{ij} , random error). ^b The diameter range within which the nonregional forest-derived equation is applicable.

For valid analyses, the equations must be presented using consistently defined variables and the three tree portions (trunk, branches, and whole-tree) must be defined consistently, which was not the case for the equations we found in the literature.

Inconsistencies encountered included the following: (1) different tree characteristic variables were used as predictors (e.g., diameter at a height of 1.37 or 1.30 m [Ker 1980]); (2) tree portions were differently defined (e.g., “bole” as the trunk portion above the stump to the height at which DOB is 10.2 cm or to the tree tip [Schlaegel 1984] or “stump” as a trunk portion below 30.5 or 30.0 cm [Alemdag 1983]); (3) equations did not include all tree components (e.g., Wittwer et al. [1999] reported the trunk biomass equations separately for bark, sapwood, and heartwood rather than as a whole for these three components together); and (4) the estimated parameters in an equation were not explicitly given in some publications (e.g., Schnell [1976] presented the equation models along with the equation-predicted biomass values, but without their estimated parameters). The inconsistencies in these equations must therefore be adjusted to be consistent with the definitions and presentations for tree portions and variables used in this study.

Based on the data and methods documented in the original publications, the acquired nonregional equations were examined and, if needed, adjusted for consistency with variable definitions and presentations in our study (see Appendix and Table 4). For the open-

grown equations, the parameters in a model for any nonregional equation were estimated using open-grown tree data in the same way as those in Table 3, and the equations are listed in Table 4.

Similar to the analyses of regional equations, the uncertainties in use of nonregional equations for estimating open-grown tree biomass were analyzed for individual trees, individual species, and the shelterbelt network.

Individual Open-Grown Trees

Biomass values for each species at each diameter and/or height of our destructively measured trees were estimated using the three sets of nonregional equations (Table 4). The three estimates for each tree portion were averaged to represent the value of the nonregional equation for that portion at that diameter and/or height. The corresponding value estimated from the open-grown equations along with its 95% CL for individual predicted values was similarly calculated using the three sets of open-grown equations. The data from destructively sampled trees along with their corresponding nonregional equation curves and open-grown equation curves with the 95% CL were plotted against diameter. Because the relative trends in the equation curves along with the 95% CL were similar to those as shown in Figure 2, we did not provide the figure; instead we summarized the relative difference between nonregional and open-grown equations (RD_{Nj}) along with coefficient of determination of

Table 5. Relative difference between nonregional forest-derived biomass and open-grown biomass equations (RD_{Nj}).

Tree portion	Green ash	Austrian pine	Eastern redcedar
Trunk			
RD_{NT} (%)	6.3 overestimation	-1.7 underestimation	14 overestimation
R^2	0.95	0.95	0.86
Branches			
RD_{NB} (%)	-51 underestimation	-29 underestimation	-31 underestimation
R^2	0.85	0.90	0.86
Whole-tree			
RD_{NW} (%)	-25 underestimation	-18 underestimation	-26 underestimation
R^2	0.95	0.98	0.83
Diameter range (cm)	5.0–42.0	3.5–39.0	5.0–31.0

RD_{Nj} is defined by model 8 where subscript j can be T , B , or W , representing trunk, branches, and whole-tree, respectively and R^2 is the coefficient of determination of fitting open-grown tree data to the model of nonregional forest-derived equation (i.e., proportion of variance explained by the equation). For each tree portion of each species, three open-grown equations corresponding to the three nonregional equations were used, which generated three R^2 values. Only the minimum value is listed for each.

fitting open-grown tree data to the model of nonregional forest-derived equation in Table 5.

Nonregional equations estimated trunk biomass of open-grown trees fairly well. Trunk biomass was slightly underestimated by 1.7% for Austrian pine and was overestimated by 6.3 and 14% for other two species (Table 5, trunk row). Similar to the regional equations, the nonregional equations significantly underestimated branch biomass of open-grown trees for all three species by 29–51% (Table 5, branch row), resulting in significant underestimation of whole-tree biomass by 18–26% (Table 5, whole-tree row).

Individual Species and the Three Species-Combined Shelterbelt Network

Biomass values of individual trees in the five segments (1, 3, 5, 7, and 9) of the shelterbelt network (Figure 1) were estimated for 2011 using the three sets of nonregional equations (Table 4). The three estimates for each tree portion were averaged to represent the portion of biomass estimated from the nonregional equations. Subsequently, the portion biomass estimates from all individual trees of one species in one shelterbelt segment were summed to represent the biomass of this portion for this species in the segment. These biomass estimates were further calculated in the same manner as for Figure 3. The corresponding estimates from open-grown equations were similarly calculated. Following the same procedure above for regional equations, the biomass estimates from the nonregional equations were compared with those from the open-grown equations for individual species and the shelterbelt network in kg per 100-m length (Figure 4).

The nonregional equations correctly estimated the trunk biomass value for Austrian pine (Figure 4A) but significantly overestimated this value by 11% for eastern redcedar (Figure 4B) and by 7.8% for green ash (Figure 4C). However, these equations significantly underestimated branch biomass for all three species by 33% (Austrian pine, Figure 4A) to 65% (green ash, Figure 4C). The paired bar patterns in Figure 4B for eastern redcedar are similar to those in Figure 4C for green ash; although the trunk biomass was overestimated, the degree of overestimation for trunk was much smaller than that of underestimation for branches. Again, the overestimation did not offset the underestimation, with whole-tree biomass for each species being significantly underestimated by 17% (Austrian pine, Figure 4A) to 28% (eastern redcedar, Figure 4B).

Looking at biomass estimates of the shelterbelt network, nonregional equations significantly overestimated the trunk biomass by

6.6% (814 kg/100-m length) but significantly underestimated the branch biomass by 59% (6,577 kg/100-m length) (Figure 4D). Similar to results for individual species, the overestimation did not offset the underestimation. The whole-tree biomass for the shelterbelt network was significantly underestimated by 28% (5,434 kg/100-m length).

Use of the Self-Fitted Forest-Derived Equations

The three nonregional equations for each tree portion by species were used to generate the three sets of biomass estimates at 1/4-centimeter intervals over the diameter range to which the equations are applicable. A self-fitted forest-derived equation (self-fitted equation) for each portion was developed by fitting the three sets of estimates to one popularly used model that expresses the biomass as a power function of diameter (Ter-Mikaelian and Korzukhin 1997). For open-grown equations, the parameters in the model of the self-fitted equations were estimated using data from open-grown trees (equations not shown). The uncertainties in use of the self-fitted equations were analyzed using the same procedures described above. The results were similar to those for the use of the nonregional forest-derived equations.

Analysis and Discussion

Figures 2–4 along with Table 5 provide a good synopsis of regional and nonregional equation performance in estimating above-ground biomass for open-grown trees. The relative trends of regional and open-grown equation curves in Figure 2 are consistent with those of the nonregional and open-grown equation curves (figure omitted). The bar pattern for pairs of biomass estimates from regional and open-grown equations in Figure 3 is consistent with that for the corresponding pairs of biomass estimates from nonregional and open-grown equations in Figure 4. These consistencies facilitate the analyses for the use of regional and nonregional forest-derived equations together.

Being similar to the use of nonregional equations, the use of self-fitted equations can be inferred from figures and discussions for nonregional equations and is not explicitly addressed in following analyses.

Trunk Biomass Estimates

Open-grown trees tend to have greater trunk specific gravity (Zhou et al. 2011) and sharper trunk taper (Sharma and Parton 2009) than forest-grown trees. If biomass gain due to greater specific gravity in an open-grown tree trunk is offset by biomass loss due to sharper trunk taper, existing forest-derived equations could be used

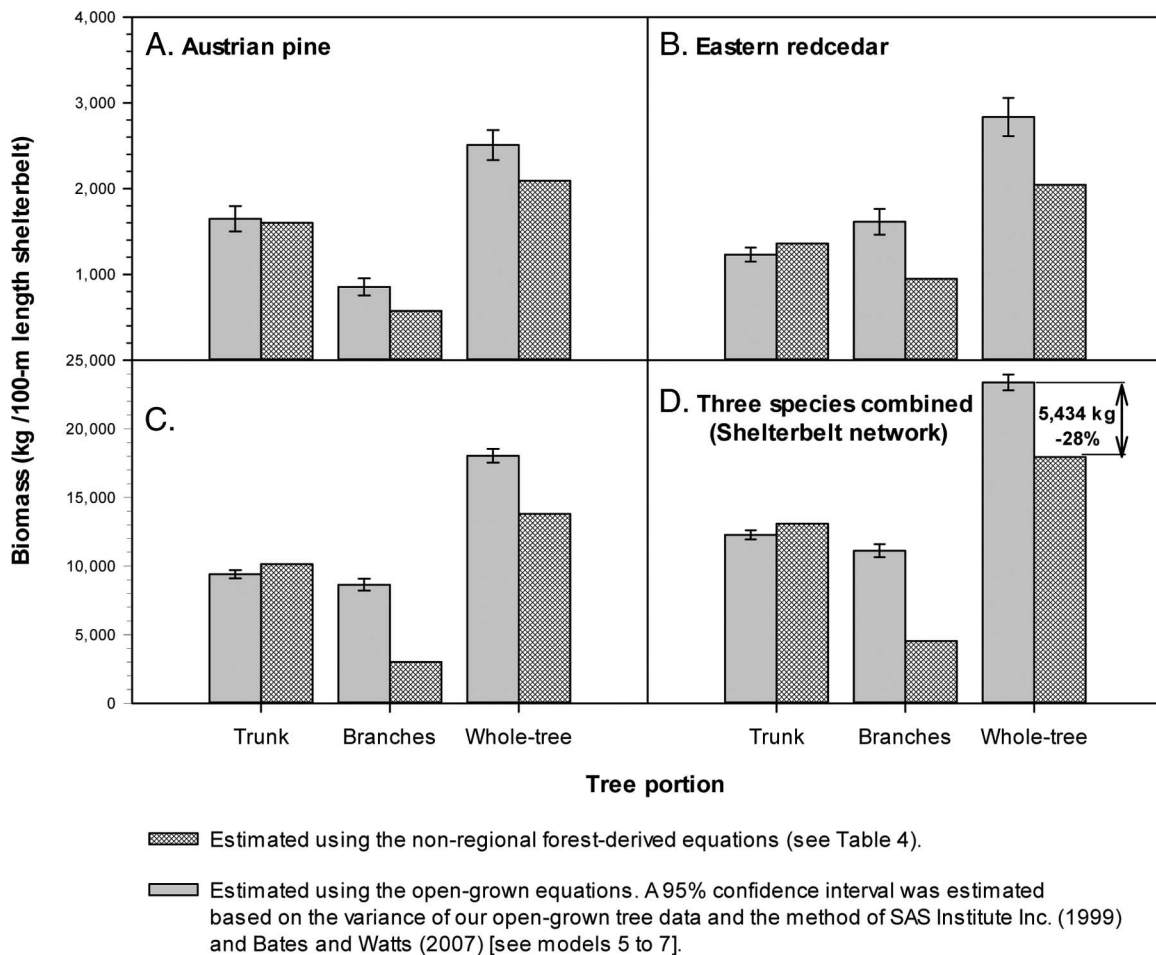


Figure 4. Comparison of nonregional forest-derived biomass to open-grown biomass equations for estimating the biomass of individual species and the three-species-combined shelterbelt network.

to estimate trunk biomass in open-grown trees. We found this to be the case with Austrian pine over the full diameter range of our study (<39 cm) (Figures 2B1, 3A, and 4A; Table 5). This was also true in the lower diameter ranges for green ash (<20 cm, Figure 2A1) and eastern redcedar (<18 cm, Figure 2C1). Using forest-derived equations, trunk biomass for green ash and eastern redcedar was significantly overestimated in the range of larger diameters (Figure 2A1 and C1). As a result of the larger diameters having greater arithmetic weight on overall trunk biomass estimates, trunk biomass was overestimated for the shelterbelt network (Figures 3D and 4D).

A tree's trunk form tapers whereas its height grows biologically in response to branching for its own mechanical stability. Because branches of Austrian pine occur in annual whorls and its main stem is less dominated by its surrounding branches in any growing condition, its taper may be less affected by open-grown conditions than the other two species. This along with greater trunk specific gravity of open-grown Austrian pine may account for forest-derived equations resulting in a reasonable estimate of trunk biomass (Figures 2B1, 3A, and 4A; Table 5).

Green ash and eastern redcedar, on the other hand, branch irregularly from any position along the trunk. In open-grown conditions, branching for these two species and especially for green ash will dominate the crown, resulting in a sharper trunk taper compared with that for Austrian pine. Eastern redcedar, although rarely losing its main stem in open conditions, branches more actively than Aus-

trian pine (e.g., the biomass ratio of branches to trunk from our data is 1.3 for eastern redcedar and 0.5 for Austrian pine), especially in the lower level of its crown. Our results suggest that early on (smaller diameters) the trunk taper of open-grown trees with this level of trunk-branch plasticity will be insignificant compared with that of forest-grown trees and/or can be offset by the biomass gain from their greater specific gravity. However, over time and as the diameters become larger, the influence of branch growth on trunk taper increases such that trunk biomass can no longer be reasonably estimated using the forest-derived equations (Figure 2A1 and C1).

Therefore, in the range of larger diameters, an open-grown trunk biomass value estimated using a forest-derived equation needs to be corrected as the equivalent estimate from the corresponding open-grown equation. This correction needs an adjustment factor of forest-derived to open-grown equation estimate [$f_{ij}(D, H \text{ or } S)$] as defined by

$$f_{ij}(D, H \text{ or } S) = \frac{M_{oj}(D, H, \text{ or } S)}{M_{ij}(D, H, \text{ or } S)} \quad (9)$$

where $M_{Oj}(D, H, \text{ or } S)$ is an open-grown equation and $M_{ij}(D, H, \text{ or } S)$ where $i = R \text{ or } N$ is a regional or nonregional forest-derived equation. By applying this adjustment factor to the biomass estimate

from a forest-derived equation, the estimate can be adjusted to reflect the biomass calculated from the corresponding open-grown equation. To develop the adjustment factor, both forest-derived and open-grown equations are needed (see model 9), but the open-grown equation is rarely available. This adjustment factor is more often needed when the open-grown equations are more unavailable. Therefore, one of our objectives in this study was to use our data to provide a basis or reference for developing a reasonable approximation of adjustment factors to extend the use of forest-derived equations to the same open-grown tree species in other regions or to more species in the same genera.

There are five pairs of forest-derived and open-grown trunk biomass equations for each of the three species in Tables 3 and 4 as well as in the equation set of self-fitted and corresponding open-grown equations (omitted). The pair of trunk equations for each species based on the model from Alemdag (1983, 1984) was excluded from adjustment factor development because both forest-derived and open-grown equations based on this model must result in the adjustment factor as a constant (Table 4) independent of diameter, height, and/or site index and were considered inappropriate equations for adjustment factor development. A pair of self-fitted and corresponding open-grown equations for each species was also excluded because the self-fitted equations were developed using three nonregional equations and thus were not independent of nonregional equations. The three remaining pairs of trunk equations were used to generate the three values of the adjustment factor at each diameter every 1/4-centimeter, using an average site index in the regional equation for each species. The three values were averaged and are shown in Figure 5A. This adjustment factor for trunk decreases with increasing diameter for all three species. For Austrian pine and eastern redcedar, it is >1.0 in the lower range of diameters, but <1.0 in the range of larger diameters. For green ash, it is <1.0 in the full range of diameters. This adjustment factor is not a constant at different diameters. Its relationship to diameter needs to be modeled.

Because height or site index adds little accuracy to a tree biomass equation (Ter-Mikaelian and Korzukhin 1997), any biomass equation [e.g., $M_{ij}(D, H \text{ or } S)$ in model 9] can be sufficiently approximated with a power function of diameter only, as given by

$$M_{ij}(D, H, \text{ or } S) \approx a_{ij1} D^{a_{ij2}} \quad (10)$$

Model 9 is therefore expressed as

$$f_{ij}(D, H, \text{ or } S) = \frac{a_{oj1} D^{a_{oj2}}}{a_{ij1} D^{a_{ij2}}} = \left(\frac{a_{oj1}}{a_{ij1}} \right) D^{(a_{oj2} - a_{ij2})} \quad (11)$$

The two terms of a_{oj1}/a_{ij1} and $a_{oj2} - a_{ij2}$ are two combinations of parameters. Each combination can be combined as one parameter, such as $b_{ij1} = a_{oj1}/a_{ij1}$ and $b_{ij2} = a_{oj2} - a_{ij2}$. As a result, the adjustment factor of $f_{ij}(D, H, \text{ or } S)$ becomes a function of diameter only, as given by

$$f_{ij}(D) = b_{ij1} D^{b_{ij2}} \quad (12)$$

With use of the data for Figure 5A, the parameters in this model were estimated for the adjustment factors of trunk and are listed in Table 6. This model fits the curves in Figure 5A well with the coefficients of determination ≥ 0.97 (Table 6).

Branch Biomass Estimates

As expected, all forest-derived equations significantly underestimated branch biomass by 29–82% for individual trees over the full

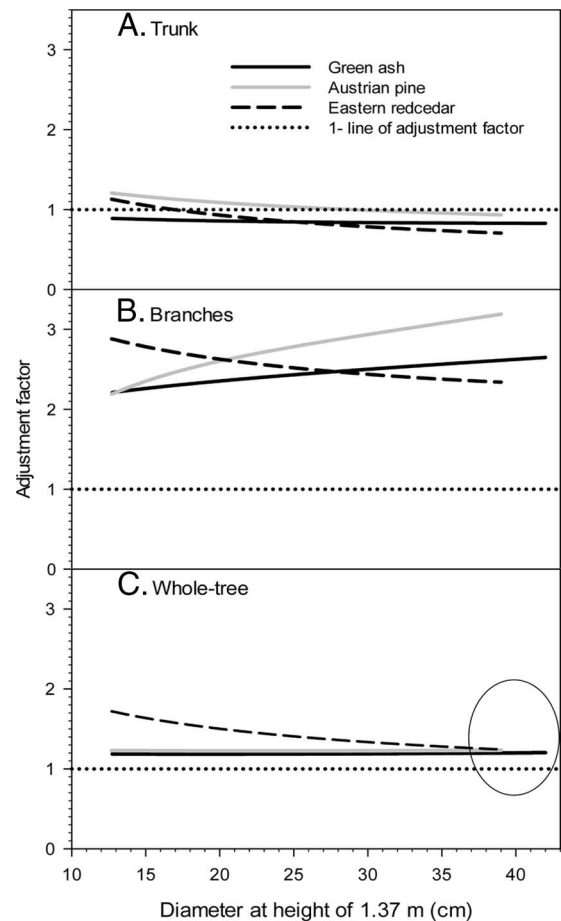


Figure 5. Forest- to open-grown tree biomass adjustment factors (an estimate ratio of open-grown biomass to forest-derived biomass equation; see models 9 and 12 for adjustment factor definition and Table 6 for curve equations).

diameter range of our studied open-grown trees (Figure 2A2, B2, and C2; Table 5) and by 33–82% for individual species (Figures 3 and 4). These underestimations resulted in the significant underestimation of branch biomass of the shelterbelt network by 67% in Figure 3D and 59% in Figure 4D.

Because trees growing in more open conditions have less competition for light, water, and nutrients than those in forest conditions, they tend to have more branches and leaves and therefore larger crowns. For instance, over the diameter range of 12 to 37 cm, the entire length of open-grown eastern redcedar supported live branches, but the live-crown length of forest-grown eastern redcedar was between 35 and 50% of total height (Wittwer et al. 1999). The biomass ratios of branches to trunk in open-grown trees were found to be 0.87 for green ash, 0.50 for Austrian pine, and 1.31 for eastern redcedar. However, in forest stands, these ratios were found to be 0.20 (Schlaegel 1984), 0.20 (Dimitrov et al. 1992), and 0.88 (Alemdag 1983), respectively.

To adjust the underestimation of branch biomass from using forest-derived equations (Figures 3 and 4), a forest- to open-grown tree biomass adjustment factor for branches of each species was calculated similarly as for trunk and is presented in Figure 5B. Model 12 was also used to fit the curves separately for the three species in Figure 5B, and the fitted parameters are listed in Table 6. This adjustment factor is much >1.0, and its minimum for the three species is 2.2. The adjustment factor increases with increasing

Table 6. Forest- to open-grown tree biomass adjustment factors.

Tree portion	Green ash			Model: $f_{Fj}(D) = b_{Fj1}D^{b_{Fj2}} + \varepsilon_{Fj}^a$ Austrian pine			Eastern redcedar		
	b_{Fj1}	b_{Fj2}	R^2	b_{Fj1}	b_{Fj2}	R^2	b_{Fj1}	b_{Fj2}	R^2
Trunk ($j = T$)	1.026	-0.059	0.97	2.161	-0.229	1.00	3.281	-0.420	0.99
Branches ($j = B$)	1.497	0.152	0.99	0.998	0.318	0.99	4.586	-0.185	0.99
Whole-tree ($j = W$) ^b	$f_{FW}(D) = 1.19 \pm 0.01$			$f_{FW}(D) = 1.23 \pm 0.02$			3.584	-0.290	0.99
Diameter range	12.7 ≤ D ≤ 42.0			12.7 ≤ D ≤ 39.0			12.7 ≤ D ≤ 32.0		

^a $f_{Fj}(D)$ is the forest- to open-grown tree biomass adjustment factor, where D (cm) is diameter at height of 1.37 m, b_{Fj1} and b_{Fj2} are parameters, ε_{Fj} is random error, and R^2 is the coefficient of determination (proportion of variance explained by the equation).

^b The adjustment factor for whole tree is not necessary if the whole tree biomass is the sum of trunk and branch biomass values that are adjusted using their corresponding adjustment factors.

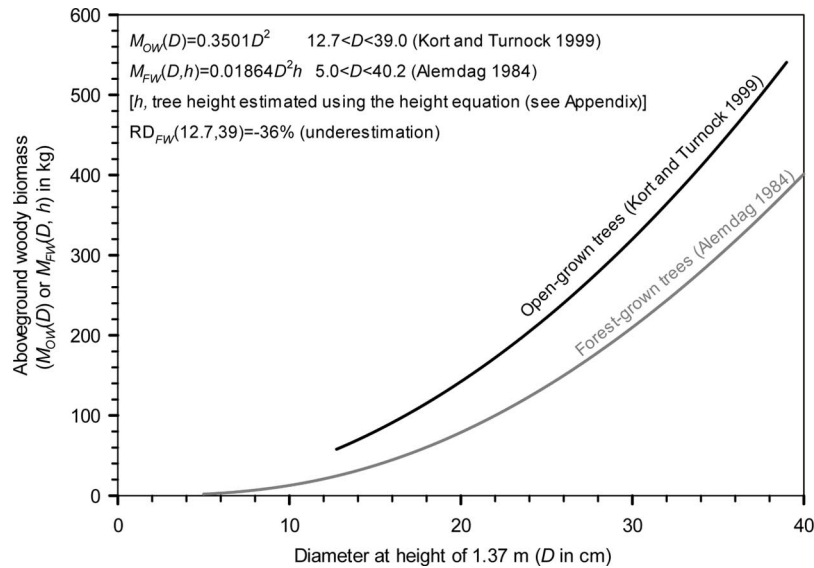


Figure 6. Comparison of a forest green ash biomass equation curve (Alemdag 1984) with a shelterbelt green ash biomass equation curve (Kort and Turnock 1999) from northern Canada.

diameter in green ash and Austrian pine but decreases for eastern redcedar. The curves for the three species in Figure 5B were also well described by model 12 with the coefficients of determination ≥ 0.99 (Table 6).

Whole-Tree Biomass Estimates

Whole-tree biomass is the sum of trunk and branch biomass estimates. According to the allometric scaling theory (Enquist and Niklas 2001), regardless of crown form or trunk-branch biomass ratio, a tree species at a given diameter maintains its biomass more or less constant by changing specific gravity within its parts and redistributing its biomass between trunk and branches to accommodate different crown forms and trunk-branch biomass ratios (Gafta and Crisan 2010). The comparison of biomass curves, particularly for green ash and eastern redcedar in Figure 2, supports this theory. As they grow, open-grown trees were found to gradually allocate less biomass to trunk and more biomass to branches than forest-grown trees. The opposite behavior in forest-grown trees is inferred by looking at the results of using the forest-derived equations. As diameter increases, the open-grown trunk and branch biomass curves diverge down and up, respectively, away from their corresponding forest-derived curves (Figure 2A1 versus A2, B1 versus B2, and C1 versus C2). As allometric scaling theory describes, open-grown and forest-derived whole-tree biomass curves tend to converge together,

with any open-grown tree equation curve still above its corresponding forest-grown equation curve at the range of larger diameters (Figure 2A3, B3, and C3). This implies that, at the same diameter, open-grown trees have more aboveground biomass than forest-grown trees. Comparison of an open-grown green ash biomass equation curve (Kort and Turnock 1999) with a forest-derived counterpart (Alemdag 1984) from northern Canada (Figure 6) also shows the same conclusion. The relative difference, as defined by model 8 and illustrated in Figure 6, was -36% . This relative difference in whole-tree biomass from our study ranges from -18 to -34% (Figures 2A3, B3, and C3; Table 5).

To compensate for the underestimation of whole-tree biomass generated by the forest-derived equations, we simulated the forest- to open-grown tree biomass adjustment factor of whole tree for each species (Table 6). For green ash and Austrian pine, the factor is nearly invariant as a constant of 1.2 (Figure 5C). For eastern redcedar, this factor decreases to this constant with increasing diameter. This factor, as shown in Figure 5C, is all above the 1-line over the full diameter range for the three study species, indicating that an open-grown tree has more biomass than its forest-grown counterpart at the same diameter.

The magnitude of this factor along with its trend depends on the degree of difference between open- and forest-grown conditions and tree species. As shown in model 9, the adjustment factor is

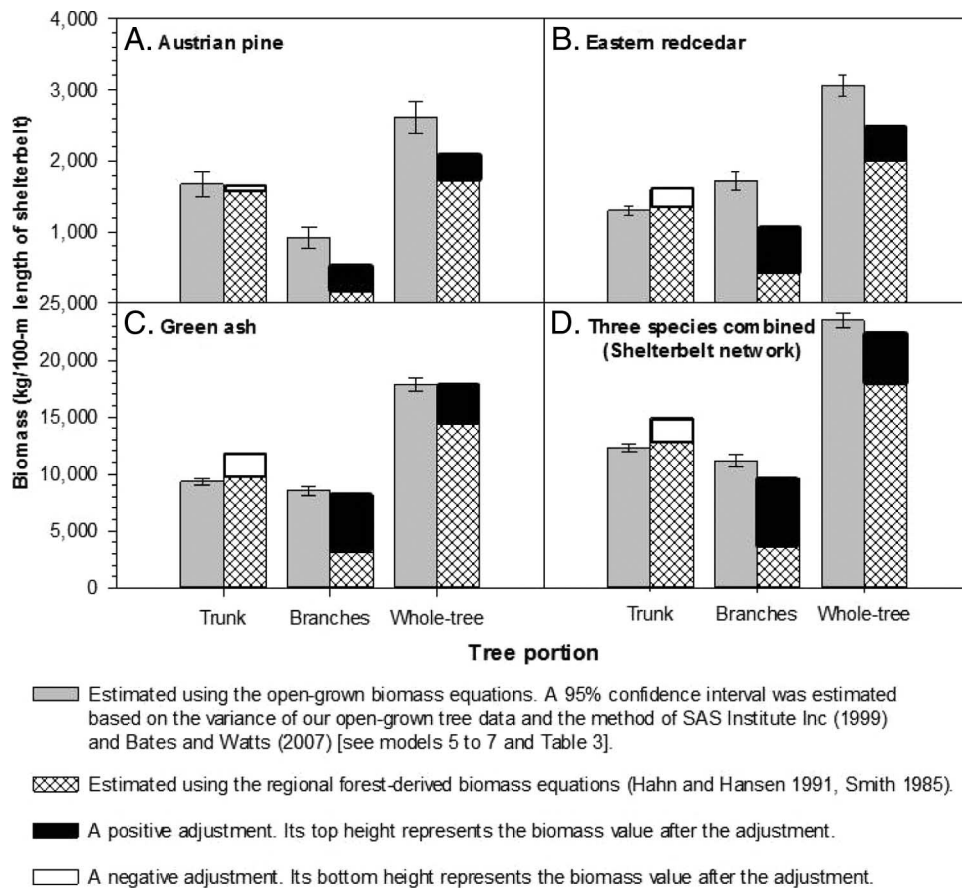


Figure 7. Application of forest- to open-grown tree biomass adjustment factors of trunk and branches to adjust open-grown tree biomass values estimated using regional forest-derived biomass equations for individual species and the three-species-combined shelterbelt (see models 9 and 12 for the adjustment factor definition and Table 6 for the adjustment factor equations).

normalized by a forest-derived equation derived using trees sampled from standard forest stands. Thus, the magnitude of the adjustment factor for a species could be reflected solely by the degree of canopy closure or openness relative to forest canopies. The open-grown trees in our study were sampled from the external rows of shelterbelts, and their open-grown conditions were similar. This may be why the adjustment factor for whole-tree biomass is a constant in green ash and Austrian pine and approaches the same constant in eastern redcedar. We could reasonably consider the growing conditions in the external rows of shelterbelt as typical open-grown conditions for tree plantings in agricultural landscapes. The adjustment factor developed using trees under such typical conditions is representative and the constant adjustment factor of 1.2 for whole-tree biomass may be more universal, making it useful for converting biomass estimates based on forest-derived equations to the estimates for open-grown tree species similar to those in our study.

Because our main interest, especially for developing carbon sequestration estimates for agroforestry systems, is the whole-tree biomass, the constant adjustment factor of 1.2 would be the adjustment factor mostly needed, although this factor for eastern redcedar is a little more than 1.2 and approaches this value with increases in diameter (Figure 5). Although it is doubtful that use of this adjustment would provide extremely accurate estimates of individual trees, it should result in more accurate estimates for a number of trees of each species or several species combined (i.e., three-species-combined shelterbelt network).

Use of Forest- to Open-Grown Tree Biomass Adjustment Factors

For each species, three adjustment factors have been developed for trunk, branches, and whole-tree. When trunk and branch adjustment factors are used, the whole-tree adjustment factor is not necessarily needed because the whole-tree biomass is a sum of trunk and branch biomass. When the whole-tree adjustment factor is used, the other two adjustment factors are not necessarily used. Therefore, the use of trunk and branch adjustment factors (two-factor adjustment) and the use of the whole-tree adjustment factor (one-factor adjustment) should be independently tested.

Two-Factor Adjustment

Trunk and branch biomass values estimated using regional equations in Figure 3 were adjusted using their corresponding adjustment factors from Table 6. The adjusted biomass values of trunk and branches were summed as whole-tree biomass without further adjustment. For smaller trees with diameter of <12.7 cm, the whole-tree biomass values without adjustment were included in the whole-tree biomass value at levels of species. The biomass values of three species were summed as the biomass value for the shelterbelt network. The adjusted biomass values of trunk, branches, and whole-tree for each species as well as for the shelterbelt network were compared with the corresponding values estimated using open-grown equations (Figure 7).

In a further comparison of Figure 7 to Figure 3, it can be seen that the adjustments effectively improved the accuracy in biomass

values of open-grown trees estimated using regional equations. For individual species, the adjustments reduced the maximum magnitude of relative errors from 26 to 6.5% for trunk, from 82 to 48% for branches, and from 33 to 21% for whole-tree. For the shelterbelt network, the adjustments reduced the magnitude of relative errors from 21 to 3.3% for trunk, from 67 to 14% for branches, and from 21 (4,823 kg/100-m length) to 4.6% (1,080 kg/100-m length) for whole-tree. All biomass values except for trunk of Austrian pine were underadjusted, which indicates that the adjustments provided conservative but improved estimations.

One-Factor Adjustment

The whole-tree biomass values estimated using regional equations were multiplied by a constant adjustment factor of 1.2 to get an adjusted whole-tree biomass value. For smaller trees of diameter <12.7 cm, the whole-tree biomass values were included in the same way as for the two-factor adjustment.

In adjusted whole-tree biomass values, the accuracy using one-factor adjustment was almost identical to the accuracy using the two-factor adjustment as shown by the pairs of whole-tree bars in Figure 7. The difference in magnitude of relative error for whole-tree biomass between the one- and two-factor adjustments is 0.8% for Austrian pine and eastern redcedar, 0.1% for green ash, and 0.2% for the shelterbelt network. If only whole-tree biomass values are needed, which is the case in most applications, the adjustment can be simplified by applying a constant adjustment factor of 1.2 to whole-tree biomass values from forest-derived equations. Whereas the existing forest-derived equations are used for a multiple-species plantation, this simple adjustment will then provide a conservative, but improved open-grown tree biomass estimate as shown by the pair of bars for whole-tree in Figure 7D with a relative difference of -4.6%.

Concluding Remarks

The growing push for greenhouse gas assessment tools at the farm, ranch, or woodlot/forest level that want to include tree-based plantings in agricultural lands requires a measurement and estimation approach that is both useful (science-based and accurate) and usable (end users will be willing and able to gather the data of variables necessary for input). Because agroforestry currently lacks the data foundation that forestry and agronomy can pull from for these activities, another requirement is finding a cost-efficient and timely means of providing the basis for carbon estimation in these systems. The motivation for this study was to address both requirements in regards to determining a suitable biomass estimation approach for these more open-grown trees.

Forest-derived equations were found to correctly estimate the trunk biomass of open-grown trees at lower diameter ranges for all three investigated species, but tended to overestimate the trunk biomass as diameter increased (Figure 2). This finding suggests that the gain in trunk biomass of open-grown trees due to their greater trunk specific gravity (Zhou et al. 2011) can offset the loss of biomass due to sharper trunk taper in the smaller but not larger diameter ranges. Over full diameter ranges, however, these forest-derived equations significantly underestimated branch biomass of individual trees by 29–82% (Figure 2; Table 5) because open-grown trees generally support larger crowns than forest-grown counterparts. As a result, forest-derived equations significantly underestimated the whole-tree biomass for these individual trees by at least 18% (Figure 2; Table 5) and thus significantly underestimated the whole-tree biomass for

individual species (minimum of 17%, Figure 4A) and for the shelterbelt network (minimum of 21%, Figure 3D).

Biomass adjustment factors (the ratio of open-grown to forest-derived biomass equation) were studied and used to correct the biases in estimation of forest-derived equations for open-grown trees using two approaches: adjusting the trunk and branch biomass values separately using the species-specific trunk and branch adjustment factors (Table 6); and adjusting whole-tree biomass values using a universal adjustment factor (1.2). Both approaches provided almost identical results for whole-tree biomass estimation. The underestimation in open-grown tree biomass values on a whole-tree basis that were estimated using the forest-derived equation was reduced from 17–33 to 0.2–20% for individual species and from 21% (4,823 kg/100-m length) to 4.6% (1,080 kg/100-m length) for the shelterbelt network (Figure 7). Based on these results, the adjustment factor of 1.2 could provide a useful, usable, and time/cost-efficient means for conservatively estimating (underestimate) open-grown tree biomass using forest-derived equations.

Whether biomass values generated by existing forest-derived equations after adjustments can be used or equations more specific to these open-grown trees in agricultural systems need to be developed will be determined by the desired and/or required level of accuracy. In light of this study, if greater accuracy is required than can be attained with this adjustment factor, developing a more sophisticated adjustment factor for the use of forest-derived equations for open-grown trees remains a more time-saving and cost-effective approach than developing open-grown equations. Our developed adjustment factors are applicable to typical open-grown trees such as our sampled edge trees. If the trees are under more open- or closed-canopy conditions, for better accuracy, a greater or smaller adjustment factor may be needed. Relating an adjustment factor to the degree of openness using crown information or some form of competition index would be another, perhaps, more accurate approach to better use forest-derived equations for open-grown trees. However, in this case, although the use of these characteristics (more variables) could improve accuracy, it could also serve as a deterrent to end users, either due to unwillingness to make that measure or inability to accurately collect data for more variables from their plantings.

At this time, it appears that the adjusted biomass estimates from forest-derived equations should be sufficient for the open-grown trees in agricultural land, given that the accuracy of adjusted whole-tree biomass for the three-species-combined estimate in Figure 7 was >95%. Obviously, the use of equations specifically developed from open-grown tree measurements is the best route to take for the greatest accuracy. However, until further research demonstrates the limitation of the approach we have presented or until the data for open-grown trees become more extensively available, the application of our approach and use of an adjustment factor is a suitable alternative.

The three species selected for this study are morphologically distinctive, providing a basis for broader use with other species used in agricultural tree plantings throughout the Great Plains. For example, the adjustment factors in Table 6 for green ash, Austrian pine, and eastern redcedar may be applicable to other *Fraxinus*, *Pinus*, and *Juniperus* species, respectively, although this inference needs additional verification.

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Appendix: Adjustment of the Nonregional Forest-Derived Biomass Equations in Table 4 Diameter

The diameter at height of 1.30 m was used in the equations by Ker (1980) and Alemdag (1983, 1984) for the three species in this study. This value needs to be replaced with the diameter at height of

Table A1. Relationship of diameter at height of 1.30 m ($D_{1.3}$ in cm) to diameter at height of 1.37 m (D in cm).

Species	$D_{1.3}(D) = a_D D + \varepsilon_D$ where ε_D is random error	
	a_D	R^2
Green ash	1.0153	99.7
Austrian pine	1.0222	99.9
Eastern redcedar	1.0164	99.9

R^2 is the coefficient of determination, or proportion of variance explained by the equation.

1.37 m. Our sampled trees were measured for diameters at the heights of 0.50, 1.0, 1.37, and 1.50 m. The diameter at height of 1.30 m can be estimated according to the trunk shape curve with height from 0.50 to 1.50 m. The shape curve in this 1-m section could be sufficiently approximated by a second-order polynomial curve. Using the four measured diameters, the trunk shape from 0.50 to 1.50 m was fit to the second-order polynomial curve in Excel for an individual tree. The diameter at height of 1.30 m was calculated using this second-order polynomial fit and related to the diameter at height of 1.37 m (Table A1). This relationship was used to replace the diameter at height of 1.30 m in an equation with the diameter at height of 1.37 m.

Stump

Biomass of full stump (30.5-cm height) was excluded from the equations by Schlaegel (1984) for green ash, and, therefore, it needs to be added to his equations. The full stump biomass was estimated using a green ash stump equation (Hahn 1984, Smith 1985). Biomass of half-stump (15.0-cm height) excluded from the equations by Perala and Alban (1994) for green ash and Austrian pine was estimated by referencing to the biomass percentage of this stump with respect to that of a full stump (Table 10 in Alemdag 1984). The estimates were used to adjust the bole equation by Perala and Alban (1994) into the trunk equation.

Top

The stem equations by Alemdag (1983, 1984) for the three species in this study and the bole equation by Schlaegel (1984) for green ash included the top biomass. The top biomass was deducted from the stem or bole equation and included as a portion of branches. Based on our data, the top biomass is independent of height and dbh because of its constant basal diameter (10.2 cm), being 6.1 ± 0.6 kg for green ash, 3.2 ± 0.7 kg for Austrian pine, and 2.8 ± 0.4 kg for eastern redcedar.

Crown Length

Wittwer et al. (1999) used diameter, height, and crown length as predictors in their equations for eastern redcedar. The crown length was positively related to biomass. For maximizing the estimates of nonregional equation in our assessment, the crown length was replaced with tree height.

Equation Presentation

Alemdag (1983, 1984) presented the equations of the three species in this study separately for stem wood, stem bark, live branches, dead branches, and twigs plus leaves for the trees with diameter of >5.0 cm. These equations define the biomass as a linear function of diameter squared times height (Table 4). Thus, any two or more

equations for different components are additive into an equation with one parameter including two independent variables: diameter and height. In addition, the twigs in “twigs plus leaves” are a portion of branches and need to be included as a part of branch total. The “twigs plus leaves” component mostly represented leaves because the equations for live limbs and dead limbs were already given separately. The woody twigs in “twigs plus leaves” must be less than half in biomass. For maximizing the estimates of nonregional equation in our assessments, half biomass of “twigs plus leaves” was used to represent the woody twig biomass and was added as a branch component. The equations for the portions: trunk, branches, and whole-tree were accordingly further adjusted for the stump and/or the top.

Schlaegel (1984), Perala and Alban (1994), and Wittwer et al. (1999) reported the equations of the three species separately for different components. These equations define biomass as a power function of diameter and/or height and cannot be added together in the same way as the equations by Alemdag (1983, 1984). An alternative approach is needed to combine the component equations into the equations for our defined portions. To combine the equa-

tions, the height in the equations of Perala and Alban (1994) and Wittwer et al. (1999) should be expressed as a function of diameter. For each species, the height-diameter relationship developed using the plot data of 1990–2011 from our study sites was used for this expression. Thus, the biomass values of each component were simulated every 1/4-centimeter over a diameter range within which the equation is applicable. With use of these simulated data, the biomass values for trunk, branches, and whole-tree were calculated and were adjusted for the biomass of stump and/or top. The biomass values for each of the three portions can be reasonably fitted to a popular model that expresses biomass as a power function of diameter (Ter-Mikaelian and Korzukhin 1997).

Schnell (1976) reported biomass models for eastern redcedar and equation-predicted biomass for different components (e.g., wood and bark) but did not report the estimated parameters for his biomass equations. The equation-predicted biomass data were combined for trunk, branches, and whole-tree. The combined data were used to estimate the parameters in the biomass equations for the three portions (Table 4).