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BIOMASS AND BIOENERGY XXX (2011) 1–11

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The use of forest-derived specific gravity for the conversion of volume to biomass for open-grown trees on agricultural land

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ARTICLE INFO

Article history:
Received 19 November 2009
Received in revised form
28 December 2010
Accepted 5 January 2011
Available online xxx

Keywords:
Carbon sequestration
Cellulosic feedstock
Eastern redcedar
Green ash
Ponderosa pine
Windbreak

ABSTRACT

Accounting for agroforestry contributions to carbon sequestration and cellulosic feedstock production requires biomass equations that accurately estimate biomass in open-grown trees. Since equations for open-grown trees are rare and developing these is expensive, existing forest-based equations are an attractive alternative for open-grown trees in carbon accounting and biomass modeling. How accurate this alternative is depends on how similar the key attributes, such as specific gravity, trunk shape, and crown architecture, are between open- and forest-grown trees. We evaluated the use of forest-derived specific gravity for conversion of volume to biomass for morphologically distinct open-grown species: green ash, ponderosa pine, and eastern redcedar. Trunk biomass was consistently and significantly underestimated from 6.3% to 16.6% depending on species, indicating open-grown trees have greater trunk specific gravity than forest-grown counterparts within the same geographic region; however a conclusive difference in branch specific gravity was not found between open- and forest-grown trees. Open-grown trees have greater trunk specific gravity, sharper trunk taper, and larger crown. When forest-based equations are used for trunk biomass of open-grown trees, the greater trunk specific gravity results in underestimation; however, the sharper trunk taper results in overestimation. Studies are needed to examine whether the underestimation could be offset by the overestimation and how the larger crown affects biomass estimation when forest-based equations are used for open-grown trees. Our results provide an essential understanding to interpret the biometric relationship of open- to forest-grown trees and to develop an efficient means how forest-based equations might be best modified for open-grown trees.

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doi:10.1016/j.biombioe.2011.01.019

Please cite this article in press as: Zhou X, et al., The use of forest-derived specific gravity for the conversion of volume to biomass for open-grown trees on agricultural land, Biomass and Bioenergy (2011), doi:10.1016/j.biombioe.2011.01.019

1. Introduction

There is a growing interest in exploiting an untapped potential of agroforestry trees for carbon sequestration [1,2] and as cellulosic feedstock for biofuel production [3,4]. Planted on agricultural land primarily for wind protection, microclimate improvement, soil and water conservation, and wildlife habitat, they have potential value in integrated efforts to meet the needs of carbon storage and energy saving while reducing carbon dioxide emissions. Tools such as COMET-VR (**C**arb**O**n **M**anagement **E**valuation **T**ool for **V**oluntary **R**eporting) [5] and C-lock (**C**arbon-lock) [6] enable individual landowners to quantify and certify market and/or trade carbon credits generated by agricultural management practices. Models like the CO2FIX (**CO_2-fix**ation) [7] or SEEDSCAPE [8] dynamically estimate the carbon sequestration potential of agroforestry practices by predicting the growth and succession of woody species under different climate and land management scenarios. Accounting or predicting carbon and bioenergy values for use in markets or for modeling efforts requires biomass equations that accurately describe tree growth and biomass under the open conditions encountered in agroforestry systems [9]. Such equations are very limited to non-existent [10,11]. In contrast, equations for tree species typically used in agroforestry systems but based on data from forest stands in forest-dominated areas (forest-based equations) are available, which renders their use for estimating the biomass of trees in agroforestry systems an attractive alternative.

A biomass equation for individual trees generally relates biomass to diameter and/or height using a model with estimated parameters [e.g., $B(D, h) = aD^bh^c + \epsilon$ where B is biomass; D diameter at breast height; h height; a, b, and c parameters; and ϵ random error]. These parameters are dependent on tree specific gravity (oven-dry weight per unit green volume) and tree architecture as described by trunk taper, crown external geometry, and crown internal structure. In a forest-based equation, these parameters are statistically estimated using data from trees sampled in forest stands in forest-dominated areas. Because tree physiognomy of the same species has been shown to differ between open versus closed canopy, forest-based equations are technically applicable only to the trees with the specific gravity and architecture that are statistically similar to the sampled trees from forest stands.

Typical forest stands have full canopy coverage generally with minimal edge effects and a maximum possible understory diversity that evolved to fully use site resources [12]. In contrast, trees in agroforestry systems are mostly grown in open conditions, such as those found in shelterbelts. These trees grow under significant edge effects with a relatively simple understory species composition. Agroforestry systems are generally designed with regular stand spacing, being subjected to more radiation, direct wind momentum load, and more agricultural residuals (i.e. fertilizers, pesticides, and irrigation). These differences in growing conditions and land management influences between forest stands and agroforestry systems could lead to differences in specific gravity and architecture between forest- and open-grown trees, bringing into a question the accuracy of using available, but forest-based equations for open-grown trees. For example, in Canada, the forest-based green ash (*Fraxinus pennsylvanica* Marsh.) equation developed by Alemdag [13] is different from the open-grown green ash equation developed by Kort and Turnock [10]. On average, over a DBH range of 12.8–39.0 cm, the forest-grow green ash biomass is 39.6% smaller than open-grown green ash biomass. Studies are needed to address how specific gravity and/or architecture can lead to differences in biomass between forest- and open-grown trees. This paper assesses the use of forest-derived specific gravities of wood and bark for the conversion of volume to biomass for open-grown trees, providing essential and crucial understanding of how existing forest-based equations might be best modified to efficiently and accurately estimate the biomass of open-grown trees.

2. Assessment approaches

Tree species groups in agricultural settings are morphologically characterized by broad-leaf, needle, or scale-like foliage. Trees in single-row or double-row shelterbelts and in external rows of multiple-row shelterbelts grow under open conditions that are typical of most temperate agroforestry systems. Representing the three foliage morphologies, the widely used tree species of green ash, ponderosa pine (*Pinus ponderosa* Laws.), and eastern redcedar (*Juniperus virginiana* L.) from the external rows of shelterbelts were selected for this study.

Directly measuring wood and bark specific gravities is a simple approach to assessment on specific gravity of open-grown trees, but expensive and time intensive. The specific gravity for the same species depends on the microclimate, site conditions, and management [14]. It also varies within the tree, being greater at the base than at the top and greater in heartwood than in sapwood. To measure the specific gravity in a tree, a number of samples from the same tree are needed. To be representative of a region, samples must be collected from a number of plots widely dispersed within the region. As an alternative to this labor-intensive and costly approach to the assessment, a statistical approach can be used if there are pre-existing data sets for biomass and volume.

The biomass of a tree can be directly measured from its green weight and moisture content (weight-measured biomass) and is considered to be a true value of the tree biomass. Therefore, the use of forest-derived wood and bark specific gravities for the conversion of volume to biomass (volume-converted biomass) can be assessed by directly comparing volume-converted to weight-measured biomass for the same tree (direct comparison method). If the volume-converted biomass is not significantly different from the weight-measured biomass, the use of forest-derived specific gravity is unbiased to this open-grown tree and the specific gravity of this tree is approximately equal to the forest-derived specific gravity. Otherwise, the use of forest-derived specific gravity either overestimates or underestimates the biomass of the open-grown tree and this tree has either smaller or greater specific gravity than the forest-grown one.

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Generally, tree measurements for biomass only include the data (e.g. the diameters, lengths, and weights of trunk sections) necessary to calculate trunk volume, but not branch volume. Therefore, the direct comparison method can be used for the trunk, but not for branches. However, assessing specific gravity with open-grown trees for the branch component is needed for overall assessment of the whole tree (referred to above-ground woody components in this study).

Fortunately, we have two sets of biomass and volume data collected by our group from shelterbelt trees that will enable us to do the assessment not only for trunk, but also for branches and eventually for the whole tree. One data set was collected as part of a study on the growth and biomass of shelterbelt trees in 2001 and 2004 (GB data) and contains trunk and branch weights along with trunk volume. The other data set was collected as part of a study on aerodynamic structure of shelterbelt trees in 1996 and 1997 (AS data) and contains both trunk and branch volume. Using the GB data, the use of forest-derived specific gravity for the conversion of trunk volume to biomass can be assessed by the direct comparison method because in GB data set, each trunk has both weight-measured and volume-converted biomass values. However, this comparison is not applicable to branches because the weight-measured biomass values of branches in the GB data set do not have corresponding volume values and the volume values of branches in the AS data set do not have corresponding weight-measured biomass values. Therefore, as an alternative, the weight-measured biomass values in the GB data set were used to develop a regression curve of weight-measured branch biomass to diameter. The use of forest-derived specific gravity for conversion of branch volume in AS data set into biomass can then be assessed against this regression curve (regression comparison method). If the volume-converted values scatter significantly either above or below the regression curve (greater or smaller than corresponding regression values), then the use of forest-derived specific gravity overestimates or underestimates, respectively, the branch biomass of open-grown trees and indicates that the branch specific gravities of open-grown trees differ from that in forest-grown trees. If the volume-converted biomass data randomly scatter above and below the regression curve, then the use of forest-derived specific gravity is unbiased and open- and forest-grown trees have statistically comparable branch specific gravities. Further, the regression curve also can be developed for the trunk and the whole tree, against which the specific gravity of open-grown trees can be assessed additionally for the trunk and even for the whole tree using this regression comparison method. The additional assessment for the trunk allows us to check the assessments for the trunk using the direct comparison method.

The use of forest-derived specific gravities for the conversion of volume to biomass for open-grown trees is assessed through two approaches: (1) direct comparison of the volume-converted to weight-measured biomass for the same individual trunks and (2) regression comparison of volume-converted biomass against the regression curve of weight-measured biomass to diameter for branches, also for trunk, and eventually for whole tree.

3. Data collection

3.1. *Field sampling and measurements*

With the assistance of USDA Natural Resource Conservation Service personnel, thirty six shelterbelts with one or more of the three selected species: green ash, ponderosa pine, and eastern redcedar were identified from fifteen counties in two states (Nebraska and Montana, USA) (Fig. 1). During the non-growing seasons of 2001 and 2004, a representative segment in each shelterbelt was selected. Each segment included 30 or more trees for each selected species and was designated as the measurement plot. The DBH [diameter at breast height (1.37 m)] and height of each tree in the plot were measured. Based on these measurements, an average single stem tree with representative crown architecture was destructively measured. If the landowner permitted, two additional trees from each species, representing smaller and larger individuals were also destructively sampled. Additionally, volume from 18 green ash trees and 13 eastern redcedar trees were measured as part of a study on aerodynamic structure of shelterbelt trees at the University of Nebraska Agricultural Research and Development Center (ARDC), Nebraska, USA in 1996 and 1997. The total number of sampled trees along with ages, DBH, and heights is given for each species in Table 1.

Tree biomass as reported by the US Forest Service Forest Inventory and Analysis (FIA) is the total oven-dry weight of the above-ground wood and bark components in a tree with diameter of 2.5 cm or greater [15]. In the FIA system, individual trees are divided into different portions: stump (a main stem portion from the ground surface to height of 30.5 cm), bole (a main stem portion above the stump up to diameter outside bark of 10.2 cm), top (above bole), live limbs, and dead limbs. For the purpose of this study, the stump and bole, including their wood and bark, are referred to as the trunk portion and the remaining excluding foliage as the branch portion.

Each sampled tree was cut near the ground surface, leaving no stump. Branches were cut flush with the stem. For each stem, length was measured to the nearest centimeter and diameters to the nearest millimeter at heights of 0, 0.5, 1.0, 1.37, and 2.24 m and thereafter at heights of every 1-m increment upward until the proximal base of the most distal section shorter than 1 m. At each measured height, a 3-cm thick disk was marked on the north side, cut off above the measured height from the stem, and kept fresh for determinations of wood and bark volumes along with ring counts and age determinations at the working surface (the bottom side of disk). The chips of wood and bark from the saw kerf were collected at each height position, at which diameter was measured, and sealed in a plastic bag for moisture determination in a laboratory. The trunk, including the samples, was weighed to the nearest 0.5 kg on a trailer scale system [three Road Weigher (Model: RW Series) scales under a trailer]. For the trees sampled in 1996 and 1997 at ARDC, moisture samples were not collected because the samples were measured only for green volume. Branches were measured using different procedures for weight and volume as described below.

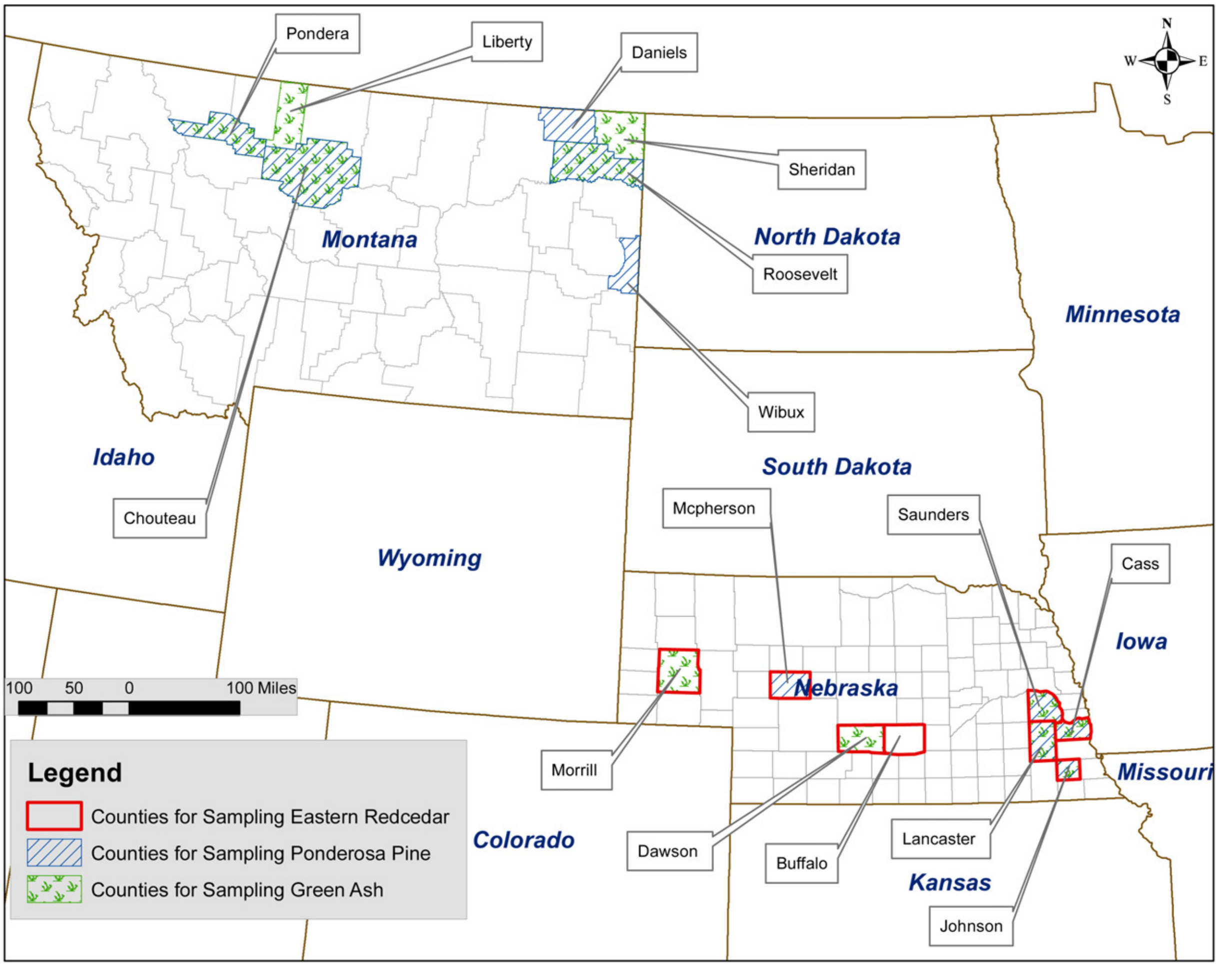

Fig. 1 – Map of counties from which open-grown trees were destructively sampled in Nebraska and Montana, USA.

3.2. *Weight-measured biomass*

All branches from each tree of green ash without leaves and of ponderosa pine and eastern redcedar with foliage were weighed on the trailer scale system. To determine the biomass of branches excluding foliage, three compound branches of different sizes (small, medium, and large), whose main limb grew directly out of the trunk including all limbs on the main limb, were sampled from each tree to estimate branch moisture content and green weight-ratio of foliage to branches. Each sample was separated into limbs and foliage if presents. The limbs were weighed to the nearest gram and the foliage to the nearest 0.1 g. For each compound branch, three segments in the main limb were taken separately from its top, middle, and base sections and sealed in a plastic bag for moisture determination in a laboratory. The green weight of branches excluding foliage for a whole tree was determined using the green weight-ratio of foliage to branches that was averaged over the three compound branch samples from that tree.

Each moisture sample was weighed and then dried to a constant weight in a forced-air oven at 65 °C. Trunk moisture content clearly showed an increase with height, most likely caused by the increasing volume-ratio of sapwood to heartwood with height. Because of trunk taper, an arithmetic average of trunk moisture content over different heights would overestimate trunk moisture and underestimate trunk biomass. Therefore, the moisture content of a sample was arithmetically weighted by the volume of the trunk section whose moisture content was represented by the sample. The weighted average moisture content of the trunk was used for the conversion of green trunk weight to trunk biomass. The limb moisture contents of three compound branch samples from one tree were averaged for the conversion of green branch weight into branch biomass of that tree.

Table 1 – Numbers, ages, DBH, and heights of sampled trees.

Species	Number of samples	Ages years	DBH cm	Height m
Green ash	40	15–54	5.9–41.6	4.1–16.8
Ponderosa pine	18	15–54	13.6–41.7	4.7–13.2
Eastern redcedar	33	6–63	1.2–30.7	2.1–13.5

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3.3. *Volume-converted biomass*

3.3.1. *Trunk*

Diameter outside the bark (DOB) on the working surface of each stem disk was measured to the nearest millimeter in the south-north and east-west directions. The measurements in the two directions were averaged to represent DOB at the height of the disk working surface. Diameter inside the bark (DIB) was similarly measured and determined. Using the values of DOB and DIB from all stem disks, the green volumes of wood and bark for this trunk were calculated using the algorithm of tree stem analysis [16]. Because bark includes void volume due to fissures, its volume was adjusted using a percentage of bark void volume of 17.7% for green ash [17], 26.0% for ponderosa pine, and 28.0% for eastern redcedar [18].

To convert the green trunk volumes to trunk biomass, specific gravities of wood and bark are needed. Specific gravity of each tree species varies geographically [14], as do biomass equations [19]; therefore, FIA develops and uses biomass equations regionally. Our research sites are located in the FIA defined region of the Central States Region that today is a part of the North Central Region [15]. The wood and bark specific gravities used in volume-converted biomass equations for the North Central Region (Table 2) were applied to our conversions.

3.3.2. *Branches*

Foliage of eastern redcedar on the branch was picked flush with each limb. The branches were separated into individual limbs, each of which is a primary branch component with two ends (one is a bud and the other is 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, the limb volume (V) was calculated using:

$$V = f\pi l(d/2)^2 \tag{1}$$

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 was estimated using the detailed measurements of 303 limbs of different sizes. Each limb was divided into at least five segments of equal length. The volume of each segment was calculated by measuring its middle diameter to the nearest 0.1 mm and length to the nearest millimeter. All segment volumes were summed into whole limb volume for determination of its volume adjustment factor. The average adjustment factor of the sampled limbs was 1.154 ± 0.026 and was used for limb volume calculations.

The green branch volume for green ash was estimated using the same methodology, which was documented in Zhou et al. [31]. In these measurements, branches did not include the main stem portion above the trunk (above the height at which DOB is 10.2 cm). In accordance with the definitions of trunk and branches in this study, the trunk and branch volume for green ash was accordingly adjusted for the purpose of this study.

Branch volume estimated by the procedure above comprises the total green volume of two components: wood and bark, both of which have different specific gravities. The branch volume for each species was separated into wood and bark volumes using the green volume-ratio of bark to wood for that species [30]. We assumed that the less obvious fissures in branch bark would not generate a void volume that caused a significant error in volume determination. Thus, the branch bark volume was not adjusted for the void bark volume. The volumes of wood and bark for branches of each species were converted to biomass using the wood and bark specific gravities used in the study region (Table 2).

4. Results

4.1. *Evaluation of volume-converted against weight-measured biomass for the same individual trunks*

The volume-converted biomass values of individual trunks were compared to corresponding weight-measured biomass values for the three studied species (Fig. 2). Data points of volume-converted biomass using regional forest-derived gravities (inverse hollow triangles in Fig. 2, panels a1, b1, and c1) were mostly below those of weight-measured biomass (solid dots in Fig. 2, panels a1, b1, and c1); therefore, the use of regional forest-derived specific gravities tended to underestimate trunk biomass. This underestimation is clearly observed in Fig. 3. Of forty eight data points for the three species in Fig. 3, forty fall below, two almost on, and only six slightly above the 1:1 line.

Degree of the underestimation can be described by the relative difference in volume-converted biomass [R_{jk}, where the first subscript variable j indicates trunk (T), branches (B), or whole tree (W) and the second subscript variable k, regionally used specific gravity (R) or greater specific gravity than regionally used (G)], given by:

$$R_{jk} = \frac{B_{Vjk} - B_{Wj}}{B_{Wj}}, \tag{2}$$

Table 2 – Summary of wood and bark specific gravities (g cm^{-3}) for the three species used in this study.

Species	North Central Region [30]		Ranges summarized from published sources				
	Trunk and branches		Trunk		Branches		Sources
	Wood	Bark	Wood	Bark	Wood	Bark	
Green ash	0.54	0.34	0.487–0.563	0.350–0.456	0.492–0.589	0.426–0.495	[20–23]
Ponderosa pine	0.38	0.34	0.380–0.460	0.310–0.350	n/a	n/a	[18,20,24–26]
Eastern redcedar	0.44	0.40	0.440–0.480	0.400	n/a	n/a	[27–29]

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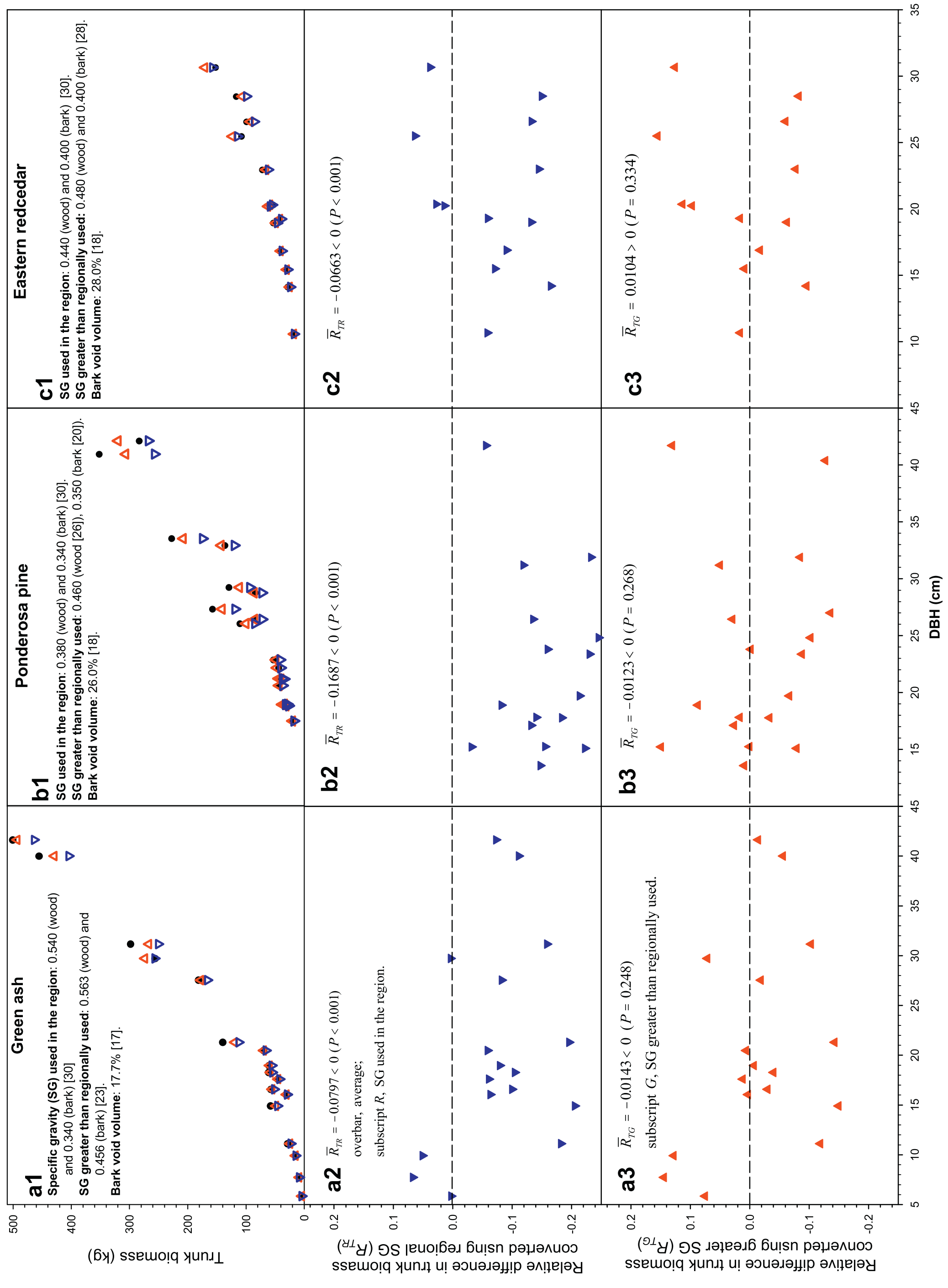

Fig. 2 – Comparison of volume-converted biomass using forest-derived specific gravity to weight-measured biomass for the same individual trunks of open-grown trees {● weight-measured biomass; ▽volume-converted biomass using forest-derived specific gravity used in the region; △ volume-converted biomass using forest-derived specific gravity greater than regionally used; ▼ the relative difference in volume-converted biomass using forest-derived specific gravity used in the region [R_{TR} as defined in eq. (2)]; and ▲ the relative difference in volume-converted biomass using forest-derived specific gravity greater than used in the region [R_{TG} as defined in eq. (2)]}.

where B_{ijk} and B_{ij} denote biomass, the subscript variable i indicates volume-converted biomass (V) or weight-measured biomass (W). The rule of subscript usages in this equation is followed throughout this paper (e.g. in Figs. 2 and 4).

The relative differences in volume-converted trunk biomass using regional forest-derived specific gravities were consistently and significantly less than zero (below the zero-line in Fig. 2, panels a2, b2, and c2) for all three species ($P \leq 0.001$). Therefore, the use of regional forest-derived specific gravities for the conversion of trunk volume to biomass for open-grown trees underestimated their trunk biomass. The averaged underestimations were 8.0% for green

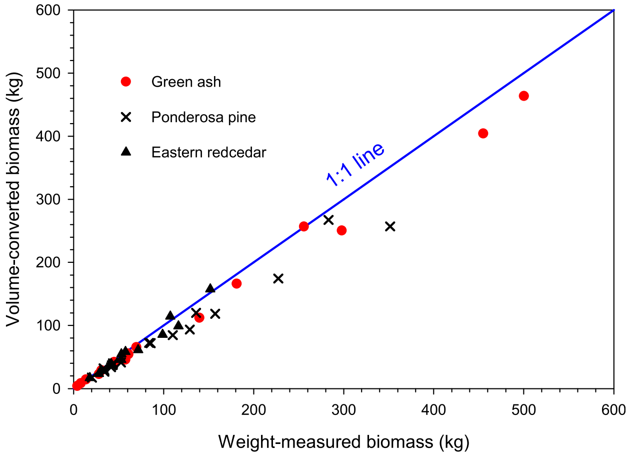

Fig. 3 – Comparison of volume-converted trunk biomass using regional forest-derived specific gravity to weight-measured trunk biomass against the 1:1 line.

ash, 16.9% for ponderosa pine, and 6.6% for eastern redcedar (Fig. 2). The underestimations indicated that in the same geographic region, open-grown trees tended to have greater trunk specific gravity than forest-grown ones.

4.2. *Evaluation of volume-converted biomass against the regression curve of weight-measured biomass to diameter*

The regression curve of biomass versus diameter for trunk, branches, and the whole tree is described generally using the biomass model [32]:

$$B_{Wj}(D) = aD^b + \varepsilon. \tag{3}$$

Using the Newton method in the NLIN Procedure of SAS© [33], the weight-based equations for trunk, branches, and whole tree of green ash and eastern redcedar were developed through estimating the parameters in this model based on weight-measured biomass values. The regression curves described by the developed equations with their 95% confidence limits for individual predicted values along with weight-measured biomass data were plotted in Fig. 4 in which the volume-converted biomass using the regional specific gravities was evaluated.

The volume-converted data for trunk biomass were generally below the regression curves for both green ash and eastern redcedar (Fig. 4, panels a1 and b1); however, those for branches scattered above and below the regression curves (Fig. 4, panels a2 and b2) while most of the data for green ash were above the regression curve. On a whole tree basis, these data closely follow the curve around (Fig. 3, panels a3 and b3).

The degree of departure in volume-converted biomass values away from the regression curve of weight-measured biomass to diameter can be evaluated using the mean disparity from the curve ($\overline{\Delta}_j$), given by:

$$\overline{\Delta}_j = \frac{\sum_{l=1}^{n}\left[B_{Vj}(D_l) - \widehat{B}_{Wj}(D_l)\right]}{n} \tag{4}$$

where the overhat indicates the regression equation of weight-measured biomass curve and n is the number of volume-converted biomass values. If volume-converted biomass data can be statistically explained by the regression curve of weight-measured biomass to diameter, the mean disparity should follow the normal distribution of $N(0, \sigma/\sqrt{n})$ where σ is the standard deviation of individual disparity values [34]. Therefore, the statistical significance in the disparity of volume-converted biomass away from the regression curve of weight-measured biomass to diameter can be tested against the t-distribution using the statistic variable given by:

$$\frac{\overline{\Delta}_j}{\sqrt{\frac{\sum_{l=1}^{n}\left[B_{Vj}(D_l)-\widehat{B}_{Wj}(D_l)\right]^2}{n(n-3)}}} \sim t(n-3) \tag{5}$$

As seen in Fig. 4, the mean disparity from the regression curve for trunk biomass was significantly less than zero for both species (panels a1 and b1), indicating that the volume-converted trunk biomass was smaller than the weight-measured trunk biomass and that the use of regional forest-derived specific gravity for the conversion of trunk volume to biomass underestimated the trunk biomass for these two species; therefore, the regression comparison arrives at the same conclusion as the direct comparison method arrived at that open-grown trees have greater trunk specific gravity than forest-grown counterparts.

The mean disparity from the regression curve for branches was significantly greater than zero for green ash (Fig. 4, panel a2), but insignificantly different from zero for eastern redcedar (Fig. 4, panel b2), indicating that the volume-converted branch biomass was greater than weight-measured branch biomass for green ash and was approximately equal to weight-measured branch biomass for eastern redcedar. The use of regional forest-derived specific gravity for conversion of branch volume to biomass overestimated the branch biomass for green ash and was unbiased for eastern redcedar; therefore, the consistent and significant difference in branch specific gravity between open- and forest-grown trees could not be found.

The mean disparity from the regression curve for whole trees is a combination of the two disparities for trunk and branches. For green ash, the negative disparity for trunk is partially offset by the positive disparity for branches. On a whole tree basis, the disparity was still negative while not statistically significant (Fig. 4, panel a3). For eastern redcedar, the significant negative disparity for trunk and the insignificant negative disparity for branches added up to a significant negative disparity for the whole tree (Fig. 4, panel b3). Therefore, the use of regional forest-derived specific gravity for conversion of whole tree volume to biomass should not result in overestimation of whole tree biomass.

5. Discussion

5.1. *Trunk specific gravity*

The three selected species were morphologically distinct from each other (i.e. broad-leaf, needle, and scale-like foliage) and represented the morphological diversity of trees used in agroforestry systems in the Great Plains and other temperate regions. Despite the morphological diversity, our results found

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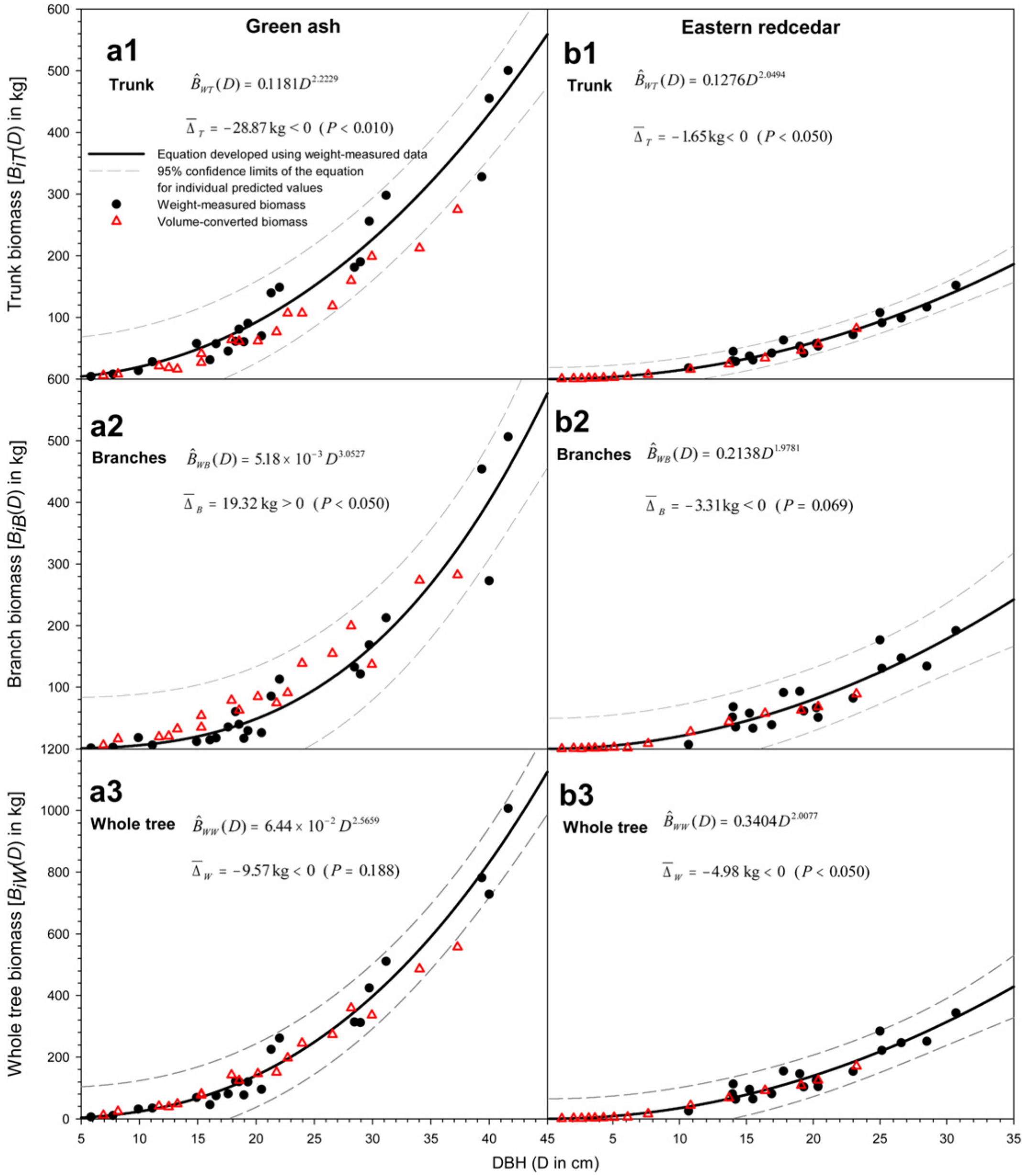

Fig. 4 – Comparison of volume-converted biomass using regional forest-derived specific gravity against the regression curve of weight-measured biomass to diameter [$B_{Wj}(D)$ is a weight-measured biomass function of diameter (D) where the subscript variable j indicates trunk (T), branches (B), and whole tree (W, trunk + branches); overhat, regression equation; overbar, mean; Δ_j, disparity of volume-converted biomass from regression curve (volume-converted biomass value minus the corresponding value on regression curve of weight-measured biomass versus diameter)].

that the trunk specific gravity within the same geographic region was consistently greater in open-grown trees than in forest-grown counterparts. This would suggest that other open-grown tree species in the region would be also most likely to have greater trunk specific gravity than forest-grown counterparts.

The greater trunk specific gravity of trees in open-grown conditions than in forest-grown conditions could be explained by the larger relative crown that is then exposed to heavier wind momentum load as would be expected for open-grown trees like those in shelterbelts which are established mainly for wind protection relative to forest-grown trees. The relative crown can be measured by the biomass-ratio of branches to trunk: the greater the ratio, the larger the relative crown. The biomass-ratios of branches to trunk were 0.62, 1.06, and 1.39 under open-grown conditions and 0.20 [23], 0.30 [35], and 0.88 [36] under forest-grown conditions for green ash, ponderosa pine, and eastern redcedar, respectively. Relative to forest-grown trees, open-grown trees support more branch weight on the same trunk biomass base. Open-grown trees must have stronger mechanical stem structure in response to the larger relative crown subject to heavier wind momentum load from open fields. This stronger mechanical stem structure must be consolidated by structural shape optimization (e.g. sharper

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trunk taper) and wood matrix solidity (e.g. increase in wood specific gravity) [37].

5.2. *Branch specific gravity*

Specific gravities for branches are unavailable for the FIA North Central Region. The FIA forest-based equations for the top (i.e. branches) in this region are weight-based equations while those for other components (e.g. trunk and stump) are volume-converted [30,38]. In this study, the same specific gravities used for the trunk were also used for the branches. Specific gravities reported for wood properties were derived from the trunk [39] and were used for the whole tree. If branches have slightly lower specific gravity than the trunk, the use of trunk specific gravity for branches overestimates branch biomass. This case is more likely to occur in green ash than in eastern redcedar because green ash has a wider range of specific gravities compared to eastern redcedar's relatively narrow range (see Table 2).

The overestimation in volume-converted branch biomass for green ash (Fig. 4, panel a2) could be explained by the possible smaller specific gravity in branches than in the trunk for individuals in this geographic region. This explanation suggests that open-grown green ash trees likely have branch specific gravity similar to forest-grown green ash trees. For eastern redcedar, the use of trunk specific gravity for branches may overestimate or underestimate branch biomass, but the biases would be most likely insignificant given the limited range in specific gravity value expressed by this species (Table 2). More definitive results could be derived with the use of branch specific gravities in the region as they become available. Based on this study, we infer that the open- and forest-grown trees may have similar specific gravity in branches within the same geographic region and the use of forest-derived specific gravity from trunk for the conversion of volume to biomass may overestimate or underestimate the branch biomass, but is unlikely to overestimate the biomass on a whole-tree basis.

5.3. *Variability in biomass data above and below the regression curves*

Variability in biomass (represented by the data points above and below any regression curve in Fig. 4) was greater for weight-measured biomass values (solid dots) than for volume-converted biomass values (upward hollow triangles). The greater variability in weight-measured biomass values may be explained by: (1) the weight-measured data being collected from the 15 counties located throughout the two states (Nebraska and Montana, USA) (Fig. 1) (2) the weight-measured branch biomass of each tree being determined based on green canopy weight converted to branch biomass using green weight-ratio of foliage to branches and moisture of branches from the three samples, each of which was a compound branch. As such for each species at given diameter, weight-measured data incorporated both the geographic variation in biomass over the 15 counties and the sampling variation in green weight-ratio of foliage to branches and in moisture of branches.

Because these volume-converted biomass values in Fig. 4 were collected only from ARDC and were the full measurements of all individual limbs for each whole tree, smaller variation was expected. Using this smaller variation as a scale [eq. (5)], we can statistically judge the difference between the volume-converted biomass and the regression curve even though the volume-converted values varied within the variation of regression (i.e. the range between 95% confidence limits of regression curve for individual predicted values in Fig. 4) that was determined by the variability of weight-measured data.

5.4. *Use of greater forest-derived specific gravities for trunk*

Forest-derived specific gravities from the North Central Region that were used for our conversion of trunk volume to biomass are in the middle-to-low limits of these species' specific gravity ranges reported from published sources (Table 2). The greater specific gravities in the top limits from these sources were alternatively tested for the conversion of trunk volume to biomass for the three species of open-grown trees whose trunk volumes were once converted to biomass using regional forest-derived specific gravities. Biomass values converted from trunk volume using the greater forest-derived specific gravities were also added to panels a1, b1, and c1 of Fig. 2 (values represented as upward hollow triangles). Each upward hollow triangle pairs with a solid dot of weight-measured biomass data. It is clear from the top three panels of Fig. 2 that the upward hollow triangles and solid dots randomly switch their relative positions above or below one another. The difference between weight-measured and volume-converted biomass using greater forest-derived specific gravity for the same trunk is not clearly consistent and must be assessed using a measure of the relative difference as defined by eq. (2).

Looking at panels a3, b3, and c3 of Fig. 2, it is seen that the relative difference randomly scatter above and below the zero-line and that the negative differences for green ash ($P = 0.248$) and ponderosa pine ($P = 0.268$) and positive difference for eastern redcedar ($P = 0.334$) were all not statistically significant. The averaged relative differences ranged from −1.43 to 1.04%, depending on species (Fig. 2, panels a3, b3, and c3). The use of greater forest-derived specific gravities for the conversion of trunk volume to biomass considerably improved the overall estimation of trunk biomass for all three species, which also indicated that open-grown trees have greater trunk specific gravity than forest-grown counterparts within the same geographic region.

Assuming that the trunk shape of open-grown trees is comparable with that of forest-grown counterparts, a forest-based and volume-converted equation as in Smith [30] and Hansen [15] would be valid for open-grown trees if the regionally used forest-derived specific gravities in the equations were replaced with the greater ones reported from other sources. Unfortunately, because trunk taper for trees under open-grown conditions, such as in agroforestry systems, is sharper than under forest-grown conditions, such a simple replacement of specific gravity is not a valid means for adapting forest-based equations to predict open-grown trees.

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The dilemma we face then is that the use of forest-based equations can result in varying levels of overestimation in trunk biomass in open-grown trees due to the sharper trunk taper of these trees while at the same time, the use of forest-derived specific gravity values in forest-based equations [15,30] tends to produce varying levels of underestimation due to the greater trunk specific gravity of open-grown trees. Further study will be needed to determine whether the overestimation could approximately offset the underestimation, making the use of forest-based trunk equations for open-grown trees a viable and efficient option.

6. Conclusion

The use of forest-derived specific gravity for the conversion of volume to biomass for open-grown trees was assessed through two approaches that compare volume-converted biomass (1) to weight-measured biomass for the same individual trunks (Figs. 2 and 3) and (2) against the regression curve of weight-measured biomass (Fig. 4). Both approaches consistently demonstrated that the use of forest-derived specific gravity for the conversion of volume to biomass significantly underestimated the trunk biomass for open-grown trees, which concluded that the open-grown trees have greater trunk specific gravity than forest-grown ones within the same geographic region. The greater specific gravity could be explained by the larger relative crown and exposure to heavier wind momentum load of open-grown trees as compared to forest-grown ones.

The use of regional forest-derived specific gravity for the conversion of branch volume to biomass for open-grown trees may either underestimate or overestimate the branch biomass. A convincing and consistent significant difference in branch specific gravity was not found between open- and forest-grown trees. As discussed in Section 4.2, we judge that the difference is most likely to be insignificant. Open- and forest-grown trees should have similar specific gravity in branches.

These findings suggest that if trunk shapes and crown architecture for the same species were statistically comparable between open- and forest-grown trees, forest-based equations would underestimate the trunk biomass for open-grown trees and would not overestimate the whole tree biomass although branch biomass might be overestimated. However, the comparison of our data for open-grown trees to the data in the literature for forest-grown trees demonstrated that both groups of trees do not share comparable trunk shape and crown architecture. Open-grown trees generally have sharper trunk taper and larger crown. When forest-based equations are used for open-grown trees, the sharper trunk taper is a factor that results in overestimation of trunk biomass and, empirically, the larger crown likely results in the underestimation of branch biomass. To use forest-based equations for open-grown trees, further studies are needed to examine how trunk specific gravity and trunk shape jointly determine the estimation of trunk biomass and what role the larger crown of open-grown trees plays in biomass estimation. The results from this study on the difference in specific gravity between forest- and open-grown trees provide essential understanding and possible approaches to how existing forest-based equations might be best modified to accurately estimate open-grown tree biomass.

Acknowledgments

A contribution of the University of Nebraska Agriculture Research Division, Lincoln, Nebraska, USA. This research was supported in part by funds provided through USDA/CSRS NRI Competitive Grants (2001-35108-10205), USDA Forest Service, Southern Research Station (Agreements: 10-JV-11330152-045), Nebraska Department of Natural Resources (Task order #10), NNSF of China (31070629), and the McIntire-Stennis Forestry Research Program. Thanks to K.A. and C.L. Messenger and H. Xu for their field work and assistance in this manuscript; USDA NRCS and Nebraska Forest Service personnel for their assistance in site selection; and the many landowners in Nebraska and Montana who permitted access to their shelterbelts.

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