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Equations for estimating aboveground biomass of cadaghi (*Corymbia torelliana*) trees in farm windbreaks

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Abstract Agroforestry systems have received global attention lately as a strategy for carbon mitigation but still are one of the least studied systems. This study was conducted in south Florida to develop biomass equations for windbreak grown cadaghi (*Corymbia torelliana*) trees and to estimate biomass in various aged windbreaks. Trees were selected for destructive sampling based on diameter at breast height (DBH) distribution from five windbreaks. Crown biomass was estimated using randomized branch sampling (RBS) and trunk biomass by taking disks every 1.5 m along the stem. Separate nonlinear equations were developed for crown, trunk and whole tree biomass estimation using DBH and height as predictors. Results indicated that DBH alone was sufficient to predict aboveground biomass, but including height in the models gave better results. Average oven-dry whole tree biomass ranged between 6 and 935 kg for 2- and 20-year-old windbreaks. Oven-dry whole tree biomass per100 m windbreak length in the same windbreaks ranged between 166 and 26,605 kg. Because fast-growing cadaghi is efficient and can produce significantly more biomass in a short period versus other windbreak species, landowners can expect higher returns from biomass or carbon trade over a shorter period, where available, to offset the cost of land occupied by the windbreaks.

Keywords Agroforestry · Allometric equation · Biomass · Randomized branch sampling · Shelterbelt

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Introduction

Global interest in carbon sequestered by agroforestry systems increased after its recognition as a greenhouse gas mitigation strategy under the Kyoto Protocol (Albrecht and Kandji 2003; Jose 2009; Nair et al. 2009; Sharrow and Ismail 2004). Such systems are becoming economic incentives for landowners with the increase in carbon (Oelbermann et al. 2004) and biomass markets. Despite their biomass production and carbon sequestration potential, agroforestry practices are not explicitly accounted for in national programs such as the Forest Inventory Analysis of the US Forest Service and the Natural Resources Inventory of the USDA Natural Resources Conservation Service (Perry et al. 2005). Agroforestry practices are also not included in many greenhouse gas mitigation reports (Schoeneberger 2009). Agroforestry has the potential to increase farm production and provides many environmental benefits. Therefore, it is considered an integrated approach to sustainable land use. Agroforestry is now considered a greenhouse gas-mitigation strategy under the Kyoto Protocol and has received wider attention as a strategy for biological carbon sequestration (Montagnini and Nair 2004; Nair et al. 2009).

Windbreaks are widely used in agroforestry across the globe. Besides primarily modifying microclimate and protecting crops, windbreaks provide multiple functions and/or products such as fruit, animal fodder, wildlife habitat, other economic and farm products and livestock odor mitigation (Tyndall and Colletti 2007). With the increasing application of windbreaks, more trees and shrubs have been introduced in agricultural systems which have increased biomass production and the carbon sequestration potential of agroforestry compared to monoculture crops (Kirby and Potvin 2007). In addition to aboveground tree components, more than half of the carbon sequestered by trees is stored in the soil (Montagnini and Nair 2004).

Most of the carbon stored in the form of biomass by plants in agricultural systems is seasonally released back to the atmosphere upon harvesting of the particular crop. When trees are incorporated into the agriculture system in the form of windbreaks, a portion of the carbon sequestered can be retained and stored for much longer periods of time as the system is not easily and quickly replaced by other practices (Schoeneberger 2009). While the stored carbon in tree biomass is cumulative over the lifetime of the tree, the effective time period can be extended by converting the wood produced from the harvested tree to durable products (Jose 2009), such as furniture or flooring.

Carbon stored in trees can easily be estimated from biomass and extensive work has been done on biomass estimation in forests as part of carbon mitigation programs (Brandies et al. 2006; Brown 2002; Jenkins et al. 2003; Vallet et al. 2006), but there is relatively little published on biomass growth and yield for tree species in windbreaks (such as Kort and Turnock 1999; Zhou et al. 2007). One of the challenges for estimating biomass in windbreaks is the lack of standard methods and procedures, because most woody biomass equations are developed from forest stands (Nair et al. 2009). The biomass equations developed for forest stands underestimate biomass in agroforestry systems (such as windbreaks) as trees in windbreaks are relatively open grown compared to forest trees (Zhou 1999). These systems are different and need to be studied because less competition and nutrient availability in agroforestry systems favor plant growth and produce higher biomass. These growth rates can be further enhanced when fast-growing species such as cadaghi (*Corymbia torelliana*) is used, which is increasingly being planted in field windbreaks around Florida farms to mitigate wind-related issues and manage citrus canker (*Xanthomonas campestris* pv. *citri*; Rockwood et al. 2008; Tamang et al. 2010). For windbreaks to be included in carbon accounting tools for agricultural lands [such as COMET VR (USDA Natural Resources Conservation Service 2005) and C-Lock (Zimmerman et al. 2005)], separate equations need to be developed to give better biomass estimates for these trees.

Allometric models are useful for predicting biomass non-destructively. There are a lot of species-specific and a few general models that use diameter at breast height (DBH; 1.37 m above the ground) and height, individually or combined, and sometimes wood density as predictor variables (Basuki et al. 2009; Jenkins et al. 2003; Williams et al. 2005). DBH is a widely used variable and explains more than 95% of the variation in aboveground biomass estimation (Williams et al. 2005). In some cases tree diameters other than DBH (such as diameter at 0.5 m height or basal diameter) are also used as predictors and considered important variables (Canadell et al. 1988; Wagner and Ter-Mikaelian 1999). For agroforestry systems, simple models may not be ideal for biomass estimation because trees in such systems provide various products for the farm. Individual components may require different types of equations or different predictor variables. Since our interest was in the aboveground biomass of cadaghi windbreaks, we used most commonly used variables (DBH and height) to develop site specific biomass models for cadaghi trees grown in Florida and to estimate biomass of various aged windbreaks.

Materials and methods

Study area

The study was conducted at C&B Farms (26°27′30″N, 80°58′46″W) near Clewiston, Florida, where single-row cadaghi windbreaks ranging between 1- and 20-year-old were planted. Some windbreaks were established and functional while others were in the early stages of development (Tamang et al. 2010). The study site is a vegetable farm where different types of vegetables and herbs have been grown for decades. The soils in the area are poorly drained Myakka sand (Sandy, siliceous, hyperthermic Aeric Haplaquods). Climate of the area is humid subtropical with average annual temperature of 23°C, average annual rainfall of 1,295 mm and annual average humidity of 76%.

Tree selection and sampling

Five single-row windbreaks of various ages (2–20 years) were selected for the study (Table 1). Four windbreaks (WB1–WB4) were established and functional, while the fifth windbreak (WB5) was young. Three windbreaks (WB1, WB2 and WB4) were oriented north–south while the other two (WB3 and WB5) were oriented east–west.

Five points were first randomly selected within each of WB1-WB3 and WB5 using the aerial image; for the shorter length windbreak (WB4), only four points were selected. The locations of the points were then identified in the field and a windbreak length of 45 m was measured toward the south from the points in WB1, WB2 and WB4, and toward the west in WB3 and WB5. The 45 m length was chosen so that at least 10 trees were included in each windbreak section. Trees in WB1-WB3 and WB5 were measured for total height, DBH and height to crown ratio in December 2007; the trees in WB4 were measured in September 2008 (Table 1). Distance between trees in all windbreak sections was also measured at ground level to estimate planting spacing.

Of 283 trees measured in the five windbreaks, approximately 25 and 33% were 10–20 and 20–30 cm in DBH, respectively (Table 2). Few trees (3.2%) were >50 cm in DBH. The number of trees 5–10 m tall was the highest (44.2%) followed by 15–20 m (19.8%) (Table 3).

Trees in all windbreaks were first grouped in six DBH classes (Table 2). Eleven trees were then selected based on the DBH distribution and destructively sampled: 1, 2, 5, 2 and 1 trees from each of the ≤10, 10–20, 20–30, 30–40, and 40–50 cm DBH classes, respectively were selected (Table 2). Relatively more sample trees were selected from DBH classes with more trees. Since larger trees were mostly in WB1, which had wide irrigation channels on either side making access limited, trees >50 cm DBH were not included in the sample.

Table 1 Number of trees (*n*), age, height, diameter at breast height (DBH), spacing between trees and height to crown ratio (CR) of five single-row cadaghi windbreaks at C&B Farms used for biomass sampling (mean value ± standard error)

Windbreak	Age (years)	Height (m)	DBH (cm)	Spacing (m)	CR
WB1 ($n = 64$)	20	17.5 ± 0.2	40.6 ± 1.2	2.5 ± 0.1	1.3
WB2 ($n = 51$)	8	10.3 ± 0.2	24.6 ± 0.7	4.9 ± 0.1	1.1
WB3 ($n = 72$)	6	8.0 ± 0.1	17.9 ± 0.4	3.3 ± 0.1	1.1
WB4 ($n = 37$)	8	10.0 ± 0.2	24.9 ± 0.7	4.5 ± 0.2	1.2
WB5 ($n = 59$)	2	4.3 ± 0.7	7.9 ± 0.3	3.9 ± 0.1	1.0

Table 2 Number of trees by diameter at breast height (DBH) class in five cadaghi windbreaks at C&B farms (number of trees selected for further sampling in parentheses)

DBH class (cm)	WB1	WB2	WB3	WB4	WB5	Total
≤10	0	0	2	0	50 (1)	52
10–20	1	9	48 (2)	5	9	72
20–30	6	36 (2)	22 (1)	29 (2)	0	93
30–40	26 (1)	6 (1)	0	3	0	35
40–50	22 (1)	0	0	0	0	22
>50	9	0	0	0	0	9
Total	64	51	72	37	59	283

Table 3 Number of trees by height class in five cadaghi windbreaks at C&B Farms (number of trees selected for further sampling in parentheses)

Height class (m)	WB1	WB2	WB3	WB4	WB5	Total
≤5	0	0	2	0	50	52
5–10	0	24	70 (3)	22 (1)	9 (1)	125
10–15	7	27 (3)	0	15 (1)	0	49
15–20	56 (2)	0	0	0	0	56
>20	1	0	0	0	0	1
Total	64	51	72	37	59	283

Height and DBH of sample trees were measured before felling. Trees were then cut at ground level. The crown was divided into two equal lengths: upper and lower crown. Crown (including branch and leaf) weight was estimated using randomized branch sampling (RBS; Gregoire et al. 1995; Valentine et al. 1984).

In RBS, the trunk as well as branches above a threshold diameter are considered branches. A segment is defined as the part of the branch between two consecutive nodes. A sequence of connected branch segments forms a path. Two paths were randomly selected in each crown section. The selection probability assigned to each branch at a node was $D^{2.67}$ (where D is the diameter) divided by the sum of the $D^{2.67}$ values of all branches emanating from the node. Cumulative selection probabilities were calculated for branches at each node. Then a random number was generated between zero and one using Microsoft Excel, the branch with the cumulative selection probability larger than the random number was selected, and the path continued into another segment. This process was repeated until a terminal branch with a diameter of 2.5 cm was obtained for sample trees with DBH $>$ 10 cm. Where trees had DBH $<$ 10 cm, the branch diameter of 2 cm was taken as terminal. The terminal branch, i.e., the sample branch, was cut off and collected. Leaves in the sample branch were excised and separate fresh weights of leaf and branch were taken in the field. The samples were transported to the lab and oven dried until constant weights were obtained. Segments associated with epicormic shoots and branches smaller than the threshold branch size along the path were noted and collected separately.

Dry weights of sample branches and leaves from each path were used to estimate tree-level oven-dry crown weights using the inflation factors obtained from the cumulative probabilities. Four crown weight estimates were obtained for each tree from each of four paths. The average of the four crown estimates was calculated for each tree to obtain an unbiased crown weight estimate per tree (Gregoire et al. 1995). Estimates from the four paths were considered independent as the interest was in tree weight prediction rather than statistical testing.

To estimate trunk weights, outside bark diameter measurements were taken at the base and then every 1.5 m along the trunk until a 2.5 cm diameter was reached. A sample disk was collected from the base and the top of each 1.5 m section. Fresh weights of the discs were taken immediately in the field. The disks were brought to the lab and soaked in water for 24 h. After 24 h, the disks were removed from water and excess water was wiped off. Their volume was determined using the water displacement method (Ilic et al. 2000). The disks were then oven dried for about a month until a constant dry weight was obtained. Density of the disks was estimated in kg/m^3 as described in Ilic et al. (2000). Density of each 1.5 m stem section was calculated as the average of the densities of the lower and upper disk of the section. This method assumes a constant taper over the tree trunk, which is a reasonable assumption for this tree species.

Outside bark volume of each 1.5 m trunk section was estimated using the conic frustum equation:

$$V = \frac{1}{12}\pi l\left(\frac{D_1^2 + D_1 D_2 + D_2^2}{10000}\right) \quad (1)$$

where V is the volume (m^3), l the segment length (m), D_1 the outside bark diameter of the lower disk (cm) and D_2 the outside bark diameter of the upper disk (cm).

Oven-dry weight of each 1.5 m trunk section was estimated by multiplying the section volume by the average density of the section. Total trunk dry weight was estimated as the sum of the dry weights of all the

Table 4 Height, diameter at breast height (DBH), and oven-dry crown, trunk and whole tree weights of cadaghi sample trees at C&B Farms (percentages in parentheses)

Windbreak	Height (m)	DBH (cm)	Oven-dry weight (kg)		
			Crown	Trunk	Whole tree
WB1	18.2	33.4	220.4 (37.7)	363.7 (62.3)	584.1
WB1	16.4	49.3	541.6 (40.6)	792.7 (59.4)	1334.3
WB2	10.1	20.8	50.9 (36.5)	88.5 (63.5)	139.4
WB2	11.1	23.5	102.4 (39.1)	159.6 (60.9)	262.0
WB2	13.7	38.3	147.9 (47.7)	162.3 (52.3)	310.2
WB3	7.7	14.0	38.8 (50.7)	37.7 (49.3)	76.6
WB3	7.6	16.1	29.6 (37.7)	49.0 (62.3)	78.6
WB3	8.7	22.6	89.1 (45.8)	105.5 (54.2)	194.6
WB4	10.0	24.8	142.4 (52.0)	131.5 (48.0)	273.9
WB4	11.2	28.2	91.4 (32.4)	191.1 (67.6)	282.5
WB5	5.2	9.0	38.2 (69.7)	16.6 (30.3)	54.8

trunk sections. Trunk and crown weight was added to obtain the whole tree weight.

Development of biomass equations

Separate DBH-based, and DBH- and height-based nonlinear models were fit for trunk, crown and whole tree data using the PROC NLIN procedure in SAS (SAS Institute Inc. 2008). All 11 sample trees were used to fit the models. The models that had the lowest root mean square error (RMSE), highest coefficient of determination (R^2) and the best fit plots were selected as the final models. The unsigned deviation (δ), also known as error of estimate, was calculated for each final model as follows:

$$d = \frac{\sum_{i=1}^{n} [(|\text{Observed} - \text{Predicted}|)/\text{Observed}]}{n} \times 100 \quad (2)$$

where n was the sample size.

To compare between DBH-based, and DBH- and height-based final models for the same tree component, the Akaike's Information Criterion (AIC), the small-sample bias corrected version of the AIC (AICC) and the Bayesian Information Criterion (BIC) were estimated.

Biomass estimation in windbreaks

The final models were then used to estimate the total oven-dry weight of trees in the windbreaks using tree variables from the sampled 45 m long windbreak sections. Estimated oven-dry weight in five windbreaks was expressed in kg weight per100 m windbreak length.

Results

Biomass allocation in tree components

Heights and DBHs of sample trees ranged from 5.2 to 18.2 m and 9.0 to 49.3 cm, respectively (Table 4). Almost all smaller trees were from WB3 and WB5, which had more than 48% weight on average in the tree crown, whereas larger trees from WB1, WB2 and WB4 had less than 41% weight in the tree crown on average. Whole tree weights generally increased with DBH. Crown and trunk weights averaged over all sample trees were 41.6 and 58.4%, respectively.

Allometric biomass equation fitting

Plots of crown, trunk and whole tree weights against DBH and height were nonlinear (Figs. 1, 2).

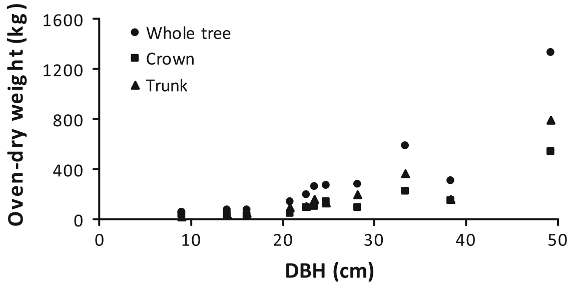

Fig. 1 Aboveground oven-dry weight vs. diameter at breast height (DBH) of sample trees at C&B Farms

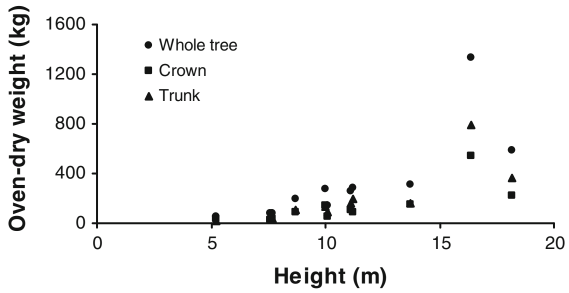

Fig. 2 Aboveground oven-dry weight vs. height of sample trees at C&B Farms

Therefore, nonlinear models of the forms in Eqs. 3–7 were initially considered as the potential models.

$$Y = b_1 X^{b2} \tag{3}$$

$$Y = b_3 / 1 + b_4 e^{-b5X} \tag{4}$$

$$Y = b_6 X^{b7X} \tag{5}$$

$$Y = b_8 b_9^X \tag{6}$$

$$Y = b_{10} e^{b11X} \tag{7}$$

where Y is the oven-dry weight of the whole tree, crown or trunk, X the predicting variable (DBH or combinations of DBH and height), and b_1–b_{11} are model parameters to be estimated.

Models were fit using DBH alone and combinations of DBH and height as predictors. Models of the form in Eq. 3 had the lowest RMSE, highest R^2 and best fit plots and were selected as the final model.

The best DBH-based crown, trunk and whole tree biomass models were:

$$Y_C = b_{12}\,\mathrm{DBH}^{b13} \tag{8}$$

$$Y_T = b_{14}\,\mathrm{DBH}^{b15} \tag{9}$$

$$Y_{WT} = b_{16}\,\mathrm{DBH}^{b17} \tag{10}$$

where Y_C, Y_T, and Y_{WT} are the oven-dry weights of the crown, trunk, and whole tree, respectively (kg), and b_{12}–b_{17} the parameters to be estimated.

The best DBH- and height-based crown, trunk and whole tree models were:

$$Y_C = b_{18}\left(\mathrm{DBH}^2 H_T\right)^{b19} \tag{11}$$

$$Y_T = b_{20}\left(\mathrm{DBH}^2 H_T\right)^{b21} \tag{12}$$

$$Y_{WT} = b_{22}\left(\mathrm{DBH}^2 H_T\right)^{b23} \tag{13}$$

where H_T is the total tree height (m), and b_{18}–b_{23} the parameters to be estimated.

Models 8 to 13 were fit using the destructively sampled tree data. Parameter estimates and fit statistics are given in Table 5. There were no noticeable trend on the spread of residuals (Fig. 3). Compared to DBH-based models, all DBH- and height-based models had smaller RMSE, but larger absolute percent deviation (δ). The absolute percent deviation (δ) ranged between 32 and 41% (Table 5). Though the models used were the best fit models, plots of observed vs. predicted crown, trunk and whole tree weights show that on an individual tree basis, crown, trunk and

Table 5 Parameter estimates, root mean square error (RMSE), coefficient of determination (R^2), unsigned deviation (δ) and *P* value from best biomass models for windbreak grown cadaghi trees at C&B Farms

Component	Eq.	Parameter	Estimate	RMSE	R^2	δ (%)	*P-value*
DBH-based models							
Crown	8	b_{12}	0.0201	50.0	0.90	33.7	<.0001
		b_{13}	2.5994				
Trunk	9	b_{14}	0.0241	84.4	0.87	32.3	<.0001
		b_{15}	2.6503				
Whole tree	10	b_{16}	0.0440	130.0	0.89	32.1	<.0001
		b_{17}	2.6297				
DBH- and height-based models							
Crown	11	b_{18}	0.00597	48.5	0.90	37.6	<.0001
		b_{19}	1.0708				
Trunk	12	b_{20}	0.00609	73.5	0.90	40.8	<.0001
		b_{21}	1.1054				
Whole tree	13	b_{22}	0.0118	116.7	0.91	39.3	<.0001
		b_{23}	1.0916				

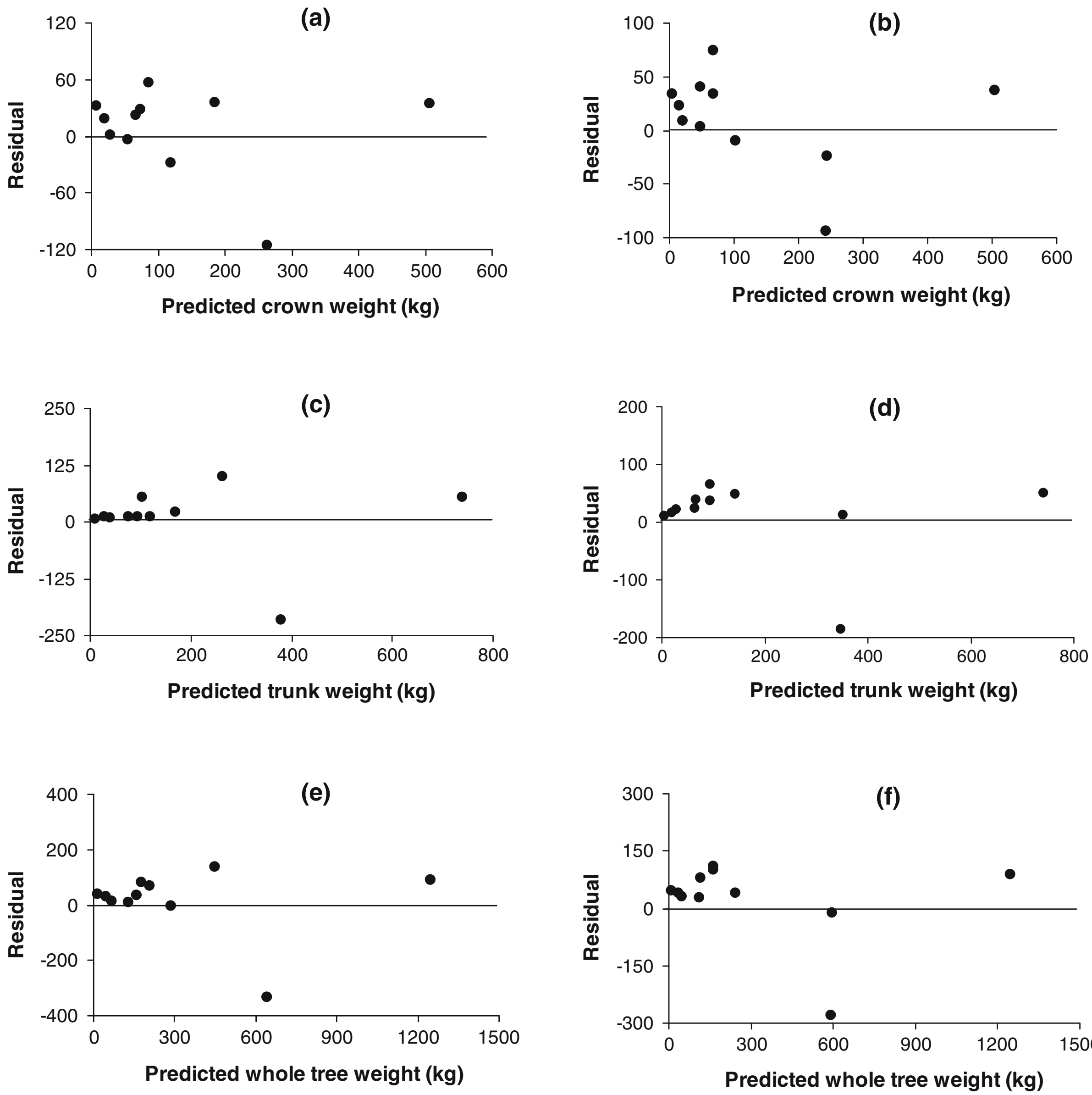

Fig. 3 Residual vs. predicted weight of crown [**a** DBH-based and **b** DBH- and height-based equations], trunk [**c** DBH-based and **d** DBH- and height-based equations] and whole tree [**e** DBH-based and **f** DBH- and height-based equations] for cadaghi trees at C&B Farms

whole tree weights were under-predicted for most trees (Fig. 4). DBH- and height-based models had slightly smaller AIC, AICC and BIC values for all tree components (Table 6).

Biomass in windbreaks

Weight partitioning into crown and trunk varied among windbreaks (Tables 7, 8). Percentage of trunk weights per tree or per 100 m windbreak length was slightly more in older windbreaks (e.g., WB1) compared to younger windbreaks (e.g., WB3 and WB5). DBH- and height-based models estimated higher whole tree, crown and trunk weight per tree or per 100 m windbreak length in WB1 trees, whereas DBH-based models estimated more weights in WB2–WB5.

Whole tree dry weight ranged between 6 and 935 kg in WB5 and WB1, respectively (Table 7).

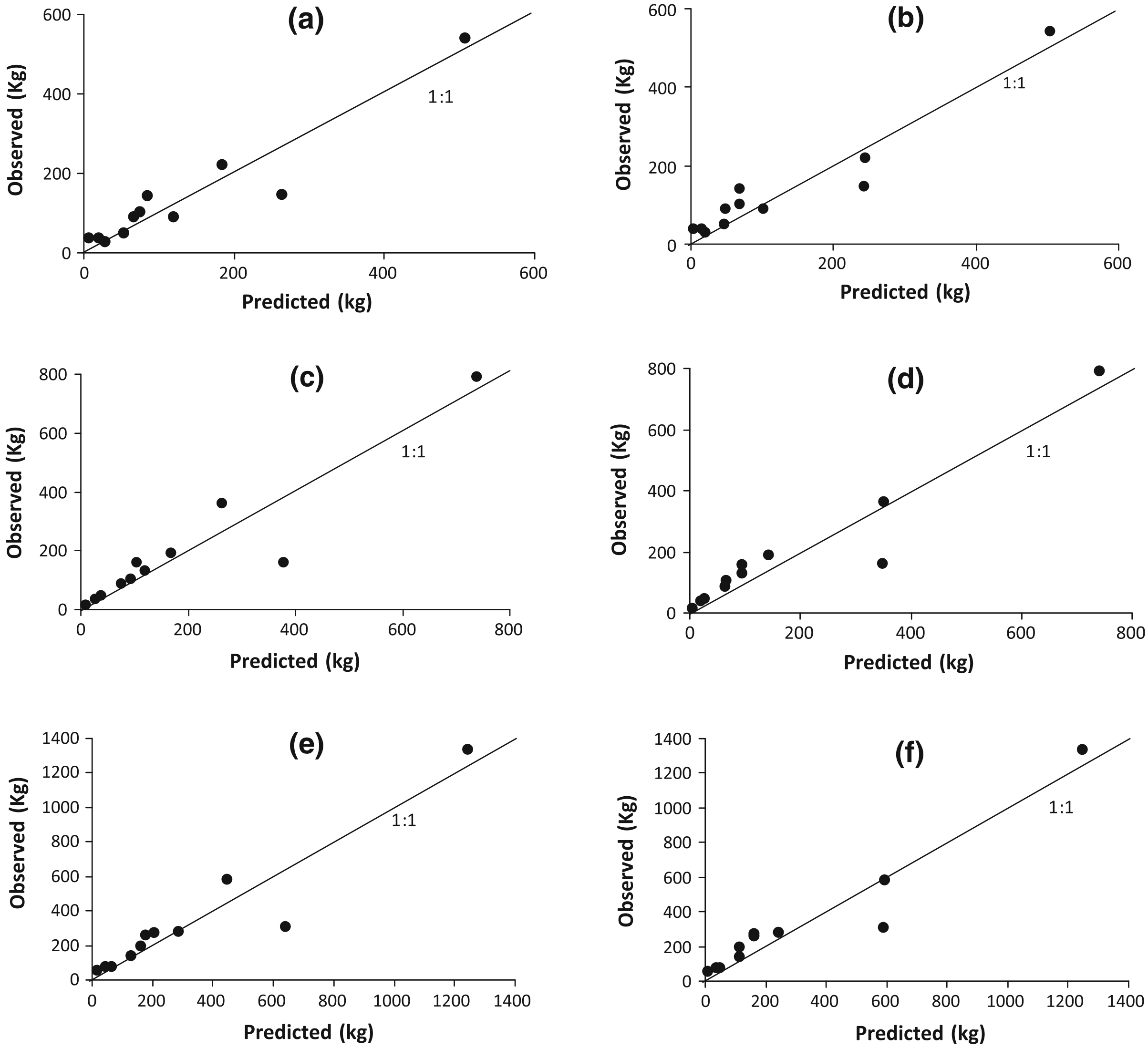

Fig. 4 Observed vs. predicted oven-dry weight of crown [**a** DBH-based and **b** DBH- and height-based equations], trunk [**c** DBH-based and **d** DBH- and height-based equations] and whole tree [**e** DBH-based and **f** DBH- and height-based equations] for cadaghi trees at C&B Farms

Whole tree dry weight per 100 m windbreak length ranged from 166 to 26,605 kg in WB5 and WB1 trees, respectively (Table 8). Crown weight ranged between 133 and 10,885 kg, and the trunk weight between 93 and 15,889 kg in WB5 and WB1 trees, respectively.

Discussion

Sample trees from older windbreaks (which had larger DBH and taller trees) generally had more trunk weight whereas smaller trees from younger windbreaks had relatively more crown weight. This could potentially be due to competition between trees in the windbreak. Smaller trees in younger windbreaks had relatively more space to grow and they also received sunlight from all sides. As the crown starts closing in, trees compete for light and growing space, shading the lower branches. As evidenced by other studies, competition for light can change tree crown shape and size which ultimately change relative allocation of biomass. Foliage was found to be generally

Table 6 Comparison between DBH-based, and DBH- and height-based final models

Component	Eq.	AIC	AICC	BIC
DBH-based models				
Crown	8	121.3	124.7	122.5
Trunk	9	132.8	136.2	134.0
Whole tree	10	142.3	145.7	143.5
DBH- and height- based models				
Crown	11	120.6	124.0	121.8
Trunk	12	129.7	133.2	130.9
Whole tree	13	139.9	143.4	141.1

concentrated in the upper part of the canopy in shade grown trees (Mar:Mohler 1947) and branchwood production was low in shade grown loblolly pine (*Pinus taeda*) (Dicus and Dean 1998). On the other hand, loblolly pines grown in sparser stands had wider and longer crowns with numerous large lower branches (Dean and Baldwin 1996). Dossa et al. (2008) also observed relatively higher weight fractions in open-grown coffee trees (*Coffea canephora* var *robusta*) compared to shade grown coffee trees.

Results of this study suggest that windbreak orientation may play a significant role in relative allocation of biomass in tree components in single-row windbreaks, but requires further study. Both WB3 and WB5 (younger windbreaks) were oriented east–west whereas WB1, WB2 and WB4 (older windbreaks) were oriented north–south. All the destructively sampled larger trees were from north–south oriented windbreaks. Because of the orientation, trees in north–south oriented windbreaks received sunlight from all sides throughout the day reducing lateral shading compared to east–west oriented windbreaks leading to potentially higher trunk biomass.

Both DBH and height were used individually and in combination to develop biomass equations to estimate tree weights in windbreaks. The smaller values of the AIC, AICC and BIC for all tree components when height was included in the models suggest that better weight estimates can be obtained from DBH- and height-based models (Table 6). DBH is the most commonly used variable in estimating trunk and whole tree weight, and is usually measured in large scale national forest inventories (Winter et al. 2008), but others have suggested using both the DBH and

Table 7 Number of trees (*n*) and average oven-dry weight per tree in five cadaghi windbreaks at C&B Farms

Windbreak	DBH-based models (kg per tree ± SE)			DBH- and height-based models (kg per tree ± SE)		
	Crown	Trunk	Whole tree	Crown	Trunk	Whole tree
WB1 ($n = 64$)	340 ± 28	495 ± 42	835 ± 70	381 ± 25	557 ± 38	935 ± 62
WB2 ($n = 51$)	91 ± 7	129 ± 10	220 ± 17	76 ± 6	106 ± 9	181 ± 15
WB3 ($n = 72$)	40 ± 2	55 ± 3	95 ± 5	30 ± 2	40 ± 2	69 ± 4
WB4 ($n = 37$)	91 ± 7	128 ± 9	219 ± 16	73 ± 5	101 ± 7	172 ± 12
WB5 ($n = 59$)	5 ± 0	7 ± 1	12 ± 1	3 ± 0	4 ± 0	6 ± 1

Table 8 Number of windbreak sections (*n*) and average oven-dry weight per 100 m windbreak length in five cadaghi windbreaks at C&B Farms

Windbreak	DBH-based models (kg/100 m windbreak length ± SE)			DBH- and height-based models (kg/100 m windbreak length ± SE)		
	Crown	Trunk	Whole tree	Crown	Trunk	Whole tree
WB1 ($n = 5$)	9,666 ± 725	14,073 ± 1,076	23,751 ± 1,801	10,885 ± 889	15,889 ± 1,300	26,605 ± 2,175
WB2 ($n = 5$)	2,061 ± 394	2,922 ± 568	4,984 ± 963	1,735 ± 340	2,407 ± 485	4,113 ± 820
WB3 ($n = 5$)	1,264 ± 111	1,763 ± 158	3,028 ± 269	944 ± 100	1,268 ± 138	2,196 ± 236
WB4 ($n = 4$)	1,863 ± 186	2,639 ± 266	4,504 ± 452	1,496 ± 146	2,067 ± 205	3,538 ± 348
WB5 ($n = 5$)	133 ± 15	178 ± 20	311 ± 35	75 ± 9	93 ± 11	166 ± 19

height for large scale applications (Jenkins et al. 2003; Lambert et al. 2005). DBH alone was found to give satisfactory results for estimating forest tree biomass, but height was a secondary variable for trunk weight estimation (Lambert et al. 2005) and it brought additional information into the estimates (Joosten et al. 2004; Vallet et al. 2006). Including height in the models increased the precision of biomass estimates of windbreak-grown Russian-olive (*Elaeagnus angustifolia*) (Zhou et al. 2007). On the other hand, height was less important for crown weight estimation (Lambert et al. 2005).

For estimating biomass in agroforestry systems, stem cross sectional area (SCSA) and circumference at breast height were used in some studies instead of using DBH directly (Dossa et al. 2008; Kort and Turnock 1999). SCSA at 1.3 m was the best predictor for aboveground weight in deciduous and coniferous species in prairie windbreaks in Canada, but including height did not improve the relationship (Kort and Turnock 1999). Stem circumference at 1.3 m and basal circumference (at 0.40 m) were the best weight predictors for *Albizia adianthifolia* grown as shade tree in shaded coffee system in Togo (Dossa et al. 2008).

Estimated whole tree dry weight (935 kg) and whole tree dry weight per 100 m windbreak length (26,605 kg) was the highest in WB1 while WB5 had the lowest. For all DBH-based models, the model-based whole tree weight predictions were within 0.1% of the whole tree weight as predicted by crown weight plus trunk weight. In the case of the DBH- and height-based equations, however, the estimates of average oven-dry crown weight plus trunk weight were approximately 0.3–1.5% higher than those from the model-based equation for WB1–WB4 and approximately 16.7% higher for WB5. For the windbreak sections as a whole, these differences were substantially less (0.6–0.7% for WB1–WB4 and 1.2% for WB5). Due to the non-linear nature of these prediction equations, we did not expect these estimates to match exactly. While we could force estimates to balance through so-called fine-tuning (i.e., manual adjustments), we elected not perform such an adjustment since, for the most part, these differences were very small.

These results indicate that fast-growing species such as cadaghi can efficiently produce more biomass as compared to other windbreak species. For example, Zhou et al. (2007) estimated weights of three Russian-olive (*Elaeagnus angustifolia*) windbreaks in eastern Montana planted in single-row and double-row with Siberian peashrub (*Caragana arborescens*). The age of the windbreaks ranged between 15 and 53 years, and the estimated whole tree weight ranged between 1,744 and 4,957 kg per100 m windbreak length for 15 and 39-year-old windbreaks. Estimated whole tree weight for a 53-year-old windbreak was only 3,636 kg per 100 m windbreak length. However, the whole tree weight of an 8-year-old cadaghi windbreak (WB2) in our study is higher than the whole tree weight observed for Russian-olive tree in windbreaks. Kort and Turnock (1999) also reported mean aboveground tree weights between 161.8 and 544.3 kg per tree for eight different species with ages between 33 and 53 years. The maximum weight of 544.3 kg per tree for 33-year-old hybrid poplar (*Populus x deltoids*) was still less than the average weight per tree observed in 20-year-old WB1 trees in the current study.

The current models may have limited application because of small sample size used in developing the models. Also, the DBH- and height-based models had smaller AIC, AICC and BIC values, but their absolute percent deviations ranged between 37 and 41%, which were higher compared to DBH-based models (range 32–34%). Higher absolute percent deviation is not surprising given the fact that the models presented here were developed using 11 sample trees. However, the models provide a good first approximation given that these trees have a limited planting distribution in Florida. This is changing, and cadaghi has now been planted in other areas in Florida. The models could possibly be improved by including more trees from a wider geographical area.

Conclusions

Both DBH and height were useful variables for estimating weights of cadaghi trees. Results suggest that including both DBH and height in the models give better weight estimates, but DBH alone can be used to get satisfactory estimates when it is the only available variable. Whole tree weights ranged between 166 and 26,605 kg per 100 m windbreak length for 2-year-old WB5 trees and 20-year-old WB1 trees, respectively. Weight estimates suggest that fast-growing cadaghi windbreaks have the potential to produce more biomass compared to other species while providing wind speed reduction and microclimate modification (Tamang et al. 2010). Therefore, windbreaks of fast-growing trees can give higher returns to landowners if carbon credits can be traded.

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