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Original article

Aboveground biomass relationships for mixed ash (*Fraxinus excelsior* L. and *Ulmus glabra* Hudson) stands in Eastern Prealps of Friuli Venezia Giulia (Italy)

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Abstract – About 5% of forest area of Friuli Venezia Giulia (Italy) is covered by mixed ash stands. In most cases, these are secondary forest established on former pastures and grasslands in the last fifty years and they constitute an important resource from an economic point of view. This paper presents allometric equations describing tree size-shape relationships for ash (*Fraxinus excelsior* L.) and wych elm (*Ulmus glabra* Hudson). Diameter at breast height explained most of the variability of the dependent variables (total stem volume, total aboveground, stem, branches and leaves biomass). Wood density variations with stem height and leaf area index (LAI) were also investigated.

biomass / LAI / allometric equation / *Fraxinus excelsior* / *Ulmus glabra*

Résumé – Biomasse aérienne chez des peuplements mélangés de frêne (*Fraxinus excelsior* L. et *Ulmus glabra* Hudson) dans les Préalpes de Friuli Venezia Giulia (Italie). Environ 5 % de la surface forestière de Friuli Venezia Giulia (Italie) est constituée de peuplements de frêne en mélange avec d'autres essences. Dans la plupart des cas, ce sont des forêts secondaires installées sur des pâturages et des prairies au cours des cinquante dernières années. Elles constituent une importante ressource économique. Cet article présente les équations allométriques pour l'estimation de la biomasse aérienne pour le frêne (*Fraxinus excelsior* L.) et pour l'orme de montagne (*Ulmus glabra* Hudson). Le diamètre à hauteur de poitrine explique la majeure partie de la variabilité des variables suivantes: volume total de la tige, biomasse aérienne totale, biomasse de la tige, biomasse des branches et des feuilles. La variation de la densité de la tige avec la hauteur et l'indice foliaire (LAI) ont aussi été considérés.

biomasse / LAI / équations allométriques / *Fraxinus excelsior* / *Ulmus glabra*

1. INTRODUCTION

Locally marginal land abandonment has been followed by afforestation and reforestation of former agricultural areas with a net increase of 14.9% of the forest area in Italy during the last fifty years [14]. In particular, the climatic and edaphic characteristics in the Prealps of Friuli Venezia Giulia (Italy) has favoured the diffusion of mixed ash stands [5]. In most cases, these are secondary forests established on former pastures or grasslands [8, 15]. There is considerable interest in estimating the biomass of these secondary forests for both practical forestry issues and scientific purposes. In particular, estimation of above-ground biomass is an essential aspect of studies of C stocks and the effects of afforestation and C sequestration on the global C balance. This study is part of a research about land use changes and carbon stocks with particular reference to secondary forests. For these reasons, the use of species-specific allometric equations is preferred because trees of different species can differ in architecture and in wood density. The harvest method is undoubtedly the most accurate method to estimate above-ground biomass [4, 13]. Allometric equations for relating tree diameter at 1.30 m (D) or other variables such as height to standing volume and biomass are commonly used for forest inventories and ecological studies. The most commonly used mathematical model to estimate biomass takes the form of a power function:

$$M = aD^b \qquad (1)$$

where M is the dry mass, D is the diameter at breast height and a and b are the scaling coefficients. The values of these coefficients are reported to vary with species, stand age, site quality, climate and stocking of stands [19]. While many equations are

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Table I. Stand characteristics of the whole area (2.4 ha) and of the plot (1000 m^2). The volume was calculated using equation (8).

		All area	Plot
Number of plants	($n\ ha^{-1}$)	1116	1000
Basal area	($m^2\ ha^{-1}$)	30.4	28.8
Volume	($m^3\ ha^{-1}$)	368	336
Mean diameter	(cm)	19	19
Mean height	(m)	21	21

reported for spruce, fir and beech stands in Alps and Prealps [3, 9, 18], no data are reported for mixed ash stands [5, 14]. As said above, because above-ground biomass is one of the most important component of total ecosystem biomass, this paper has focused on species-specific allometric equations for mixed ash secondary forests and in particular the main objectives were: (a) to characterize wood density and its variation with height; (b) to obtain an equation for predicting wood volume; (c) to obtain allometric equations for predicting total biomass and biomass of the different tree fractions (i.e. leaves, twigs, stem and branches); (d) to relate leaf area with basal area.

2. MATERIALS AND METHODS

2.1. Study area

All data were collected in a uneven-aged mixed ash stand in Taipana (Udine, Friuli Venezia Giulia, Italy) at 600 m a.s.l. (46° 12' S, 13° 20' E). The mean annual temperature is 10° C and the annual rainfall is about 2500 mm. The stand occupies an area of 2.4 ha and was partially used in the past as grassland. The forest is dominated by ash (*Fraxinus excelsior* L.) (number of trees = 77%) with the presence of wych elm (*Ulmus glabra* Hudson) (5%), bird cherry (*Prunus avium* L.) (4%), alder (*Alnus glutinosa*) (4%), broad-leaved lime (*Tilia platyphyllos* Scopoli), chestnut (*Castanea sativa* Miller) and some individuals of sycamore (*Acer pseudoplatanus* L.). After the measurement of the diameters at breast height on the entire area, a subplot of 50 × 20 m was chosen to conduct the biomass study on the species with a presence more than 5% (Tab. I). Within this area, the main species were *Fraxinus excelsior* L. (77%) and *Ulmus glabra* Hudson (21%). Tree position, diameter at breast height, total height, crown base height and two crown diameters were measured.

2.2. Data collection

To develop an allometric equation, trees were selected based on their D, H and species. Fifty-three trees (40 ash and 13 wych elm) distributed in the different classes of diameter were cut (Fig. 1).

Diameter at breast height and diameters every 1 m from the base to the top of each tree were measured and tree height was measured with a measuring tape after cutting. Round sections of wood (3–5 cm thickness) were cut from the base and at 1.30 m to calculate wood density. From six ash trees, round sections were collected every 2 m till 18 m height.

Each tree was divided into three fractions: (1) leaves; (2) twigs (D < 3 cm); (3) stem and branches (D > 3 cm). Crown (leaves and twigs) fresh weight was recorded in the field. Three subsamples of twigs with leaves were collected from 28 plants (19 ash, 9 wych elm). Twigs and leaves were stored separately in sealed plastic bags to prevent the loss of moisture. Wet weights were recorded immediately upon arrival in the laboratory. Then, the collected material was kept at 3–4 °C for the analysis.

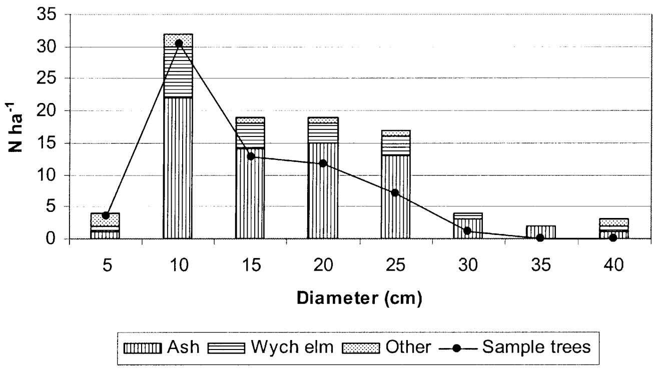

Figure 1. Number of trees per hectare of tree diameter at breast height (D) and number of sampled trees for each diameter class.

2.3. Wood density

Because wood weight and volume vary with moisture, wood density was expressed as the ratio between dry weight (P_0) and fresh volume (V_f) (i.e. volume with more then 30% of moisture). Wood density was calculated using the round sections collected at the base and at breast height. Fresh volume (wood + bark) was measured by immersion in water and dry weight was measured after drying wood at 105 ± 2 °C for 48 h.

The round sections collected at different heights were used to study the density variation with the height.

2.4. Volume and biomass calculations

Stem and branches dry biomass was calculated using volume V_i of tree stem and wood density ρ_b:

$$B_s = V_i \rho_b. \quad (2)$$

Stem volume V_i was calculated using the Heyer's formula which is based on volumes v_i of the n wood cylinders with 1 m height:

$$V_i = (S_1 + S_2)/2 + (S_2 + S_3)/2 + ... + (S_{n-1} + S_n)/2$$
$$= (S_1 + S_n)/2 + S_2 + S_3 + ... + S_{n-1} \quad (3)$$

where S_1, S_2, …, S_n are the areas at the base of each cylinder and S_n is the area at the top of last cylinder n.

Twigs biomass B_{0t} was estimated as follows:

$$B_{0t} = F\ c\ k_t \quad (4)$$

where F is the crown fresh weight (twigs + leaves), c is the mean ratio between twigs fresh weight and total weight of subsamples (leaves + twigs), k_t is the mean ratio between twigs dry weight and fresh weight measured on subsamples collected in field.

Similarly, leaves biomass B_{0l} was estimated as follows:

$$B_{0l} = F\ c\ k_l \quad (5)$$

where k_t is the mean ratio between leaves dry weight and fresh weight measured on subsamples collected in field. The sum of equation (4) and equation (5) gives total crown biomass.

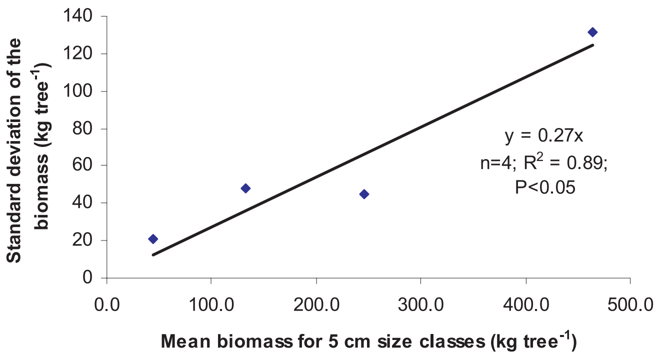

Figure 2. The standard deviation of tree biomass for 5 cm diameter size class as a function of the mean biomass for 53 sample trees.

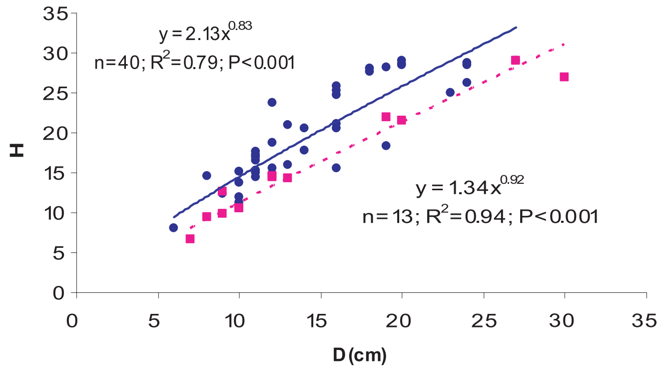

Figure 3. Relationship between diameter at breast height (D in cm) and total height (H in m). (● ash and ■ wych elm; solid line is ash, dashline is wych elm).

2.5. Leaf area

Fresh leaves subsamples (n = 84) were used to measure leaf area (cm^2) by a LiCor 3000 (Li-Cor, Lincoln, Nebraska). After drying at 70 °C for 48 h, dry weight was measured and mean specific leaf area for each species estimated (SLA = leaf area/dry weight). So, total leaf area (LA_i) from each tree was estimated as follows:

$$LA_i = B_{0li} \times SLA \quad (6)$$

where B_{0li} is the biomass of the dry leaves of the tree. Using measured crown radius, crown projection area was calculated and leaf area index (LAI = leaf area/crown projection area) was computed.

2.6. Choosing a functional form for volume and allometric equations

Volume was estimated using the following equation:

$$V = m\,(D^2H) \quad (7)$$

where m is the scaling coefficient, D is the diameter at breast height and H is the total tree height. Measured volumes were also compared with those derived from the generic volume table for broad-leaved species of Friuli Venezia Giulia [6]. Preliminarily, an equation was derived from this table in order to allow tree volume estimates for each diameter class:

$$V = -0.0016437 + 0.0000372\,D^2\,H + 0.0009616\,D - 0.0002393\,H \quad (8)$$

D is expressed in cm and H in m.

Allometric biomass equations aim to relate tree biomass to quantities that can be easily measured on trees in the field. As said above, the most commonly used functions are power models (1). That is equivalent to:

$$\text{Log}\,(B) = \log\,(a) + b\,\log\,(D). \quad (9)$$

This transformation is appropriate when the standard deviation of B at any D increases with D (Fig. 2) [19]. When this situation exists, it implies that values of B can be measured more precisely at low than at high values of D. Even though the logarithmic equation is mathematically equivalent to equation (1), the same is not true in a statistical sense [13, 18]. In fact, using equation (9) produces a systematic overestimation of the dependent variable B when converting ln (B) back to the original scale B. Many procedures to correct this difference have been advocated [1, 2, 16]. In the present study, at first equation (1) was transformed into linear regression equation (Eq. (9)) to estimate a and b by least square procedure. To avoid the over-estimation of B using the calculated coefficients, if one assumes an additive error term in the original data, then predictions should be based on nonlinear functions [13, 18]. So, in the second step, the two parameters in equation (1) were determined performing a non-linear regression by a modified Gauss-Newton iterative method in STATA 7.0 (©STATA Corporation, College Station, Texas, USA).

To estimate leaf area a linear model was used [10]:

$$LA = c\,G \quad (10)$$

where c is a scaling coefficient and G is the tree basal area (cm^2). Leaf area index (LAI) was calculated as total leaf area per m^2 of crown projection area calculated using measured crown diameters.

3. RESULTS

3.1. Plants characteristics and wood density

In Table I, dendrometric characteristics of the whole area and the study plot are reported. The relationship between diameter at breast height and total height is shown in Figure 3 (ash: $n = 40$, $R^2 = 0.79$, $P < 0.001$; wych elm: $n = 13$, $R^2 = 0.94$, $P < 0.001$).

The mean wood density is 637 ± 126 $kg \cdot m^{-3}$ for ash ($n = 70$) and 592 ± 102 $kg \cdot m^{-3}$ for wych elm ($n = 21$). Ash wood density at first decreases with height and then increases achieving its maximum at 18 m (Fig. 4). Although the trend is significant ($R^2 = 0.50$, $P < 0.01$), density values at 0 and 18 m are not statistically different (one-way ANOVA: $P > 0.05$). Table II shows the mean values of c, k_t, k_l, moisture content and SLA for the two species and Table III shows the biomass data of the 53 trees cut and weighted for this study.

3.2. Allometric equations

Using data in Table III to estimate parameters of equation (7) led to the following model for trees ($6 < D < 30$ cm) in ash mixed stand (all species together; Fig. 5a):

$$V\,(m^3) = 0.40\,D^2H \qquad n = 53;\ R^2 = 0.97;\ P < 0.001$$

D and H are expressed in m.

Table II. Mean ratio between twigs or leaves fresh weight and total weight of subsamples (c), mean ratio dry weight and fresh weight measured on subsamples collected in field (k), moisture content (M) and specific leaf area (m^2 kg^{-1}; SLA).

	Samples		c		k		M	SLA	
	Ash	Wych elm	Ash	Wych elm	Ash	Wych elm	%	Ash	Wych elm
Branches and stem	70	21	–	–	0.56 ± 0.02	0.58 ± 0.02	59 ± 12%	–	–
Twigs	19	9	64 ± 2%	68 ± 2%	0.53 ± 0.02	0.50 ± 0.02	92 ± 11%	–	–
Leaves	19	9	36 ± 3%	32 ± 3%	0.32 ± 0.03	0.29 ± 0.03	238 ± 37%	13.8 ± 3.7	22.4 ± 4.5

Table III. Biomass data (total values) of the 53 trees cut and weighted for this study. Biomass data in kg.

Diameter (cm)	No. of trees		Ash				Wych elm			
	Ash	Wych elm	Total	Stem	Twigs	Leaves	Total	Stem	Twigs	Leaves
5	1	1	8.0	6.9	0.7	0.4	12.7	6.0	4.8	1.8
10	17	7	64.8	49.5	1.6	13.7	48.5	30.7	4.5	13.2
15	10	1	156.0	134.0	3.5	18.5	57.1	49.6	5.4	2.1
20	7	2	278.3	253.0	5.4	19.8	197.0	181.2	9.0	6.9
25	5	1	440.6	406.3	9.5	24.8	587.9	570.2	12.8	4.9
30	0	1	0.0	0.0	0.0	0.0	553.3	529.5	17.2	6.6
Total	40	13	947.6	849.6	20.8	77.2	1456.5	1367.1	53.7	35.6

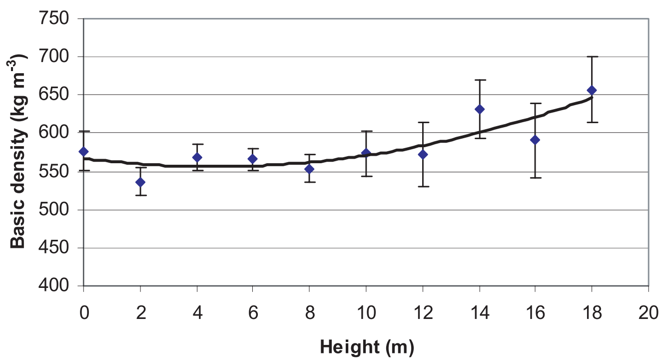

Figure 4. Wood density (wood + bark) versus height (ash only). $Y = 0.50x^2 - 4.64x + 566.93$, $R^2 = 0.74$, $P < 0.01$.

The measured volumes are well predicted by the generic table for broad-leaved species in Friuli Venezia Giulia (Fig. 5b).

Applying the model to all the trees within the plot, the total volume is 414 m^3 ha^{-1} against the 396 m^3 ha^{-1} estimated using equation (8).

The standard deviations of B at any D increases in proportion to the value of D (heteroscedasticy; Fig. 2) and so equation (9) can be used to estimate dry biomass. Results are reported in Table IV. Strong relationships were found between D and dry biomass for all the tree compartments (in Fig. 6 relationship between ln B and ln D is reported). The addition of H in the equation did not contribute to increase R^2.

As far as the non-linear regression method is concerned, estimated coefficients are reported in Table V. Also in this case, the relationships were all statistically significant.

Applying the coefficients estimated with log-transformed method (Tab. IV), the total dry biomass is 283 t ha^{-1} (stem and branches: 274 t ha^{-1}; twigs: 6 t ha^{-1}; leaves: 3 t ha^{-1}), while using coefficients reported in Table V (non-linear regression method), total biomass is 263 t ha^{-1} (stem and branches: 251 t ha^{-1}; twigs: 9 t ha^{-1}; leaves: 3 t ha^{-1}).

As far as leaf area is concerned, equation (10) becomes:

Ash: $LA = 0.14\ G$ $n = 40$, $R^2 = 0.66$; $P < 0.001$

Wych elm: $LA = 0.23\ G$ $n = 12$, $R^2 = 0.64$; $P < 0.001$.

Applying these models at stand level (1000 m^2), total leaf area is 4546 m^2 corresponding to a leaf area index (total leaf area per m^2 of crown projection area) of 3.7.

4. DISCUSSION AND CONCLUSION

Wood density values found are similar to those reported by Nardi Berti [12] and by Le Goff et al. [11]. Ash wood density trend (Fig. 4) is similar to beech and European alder that shows a density decrease from 0 to 4–5 m height and then an increase to value similar (beech) or higher (alder) at the top [7]. Anyway, if base and top values are confronted, they are not statistically different (one-way ANOVA: $P > 0.05$). Measured volumes are comparable with those derived from generic table for broad-leaved species of Friuli Venezia Giulia (Fig. 5b) and the total volumes per hectare estimated using the two methods are similar and in accordance with values reported by Guidi et al. [8] and Del Favero et al. [5].

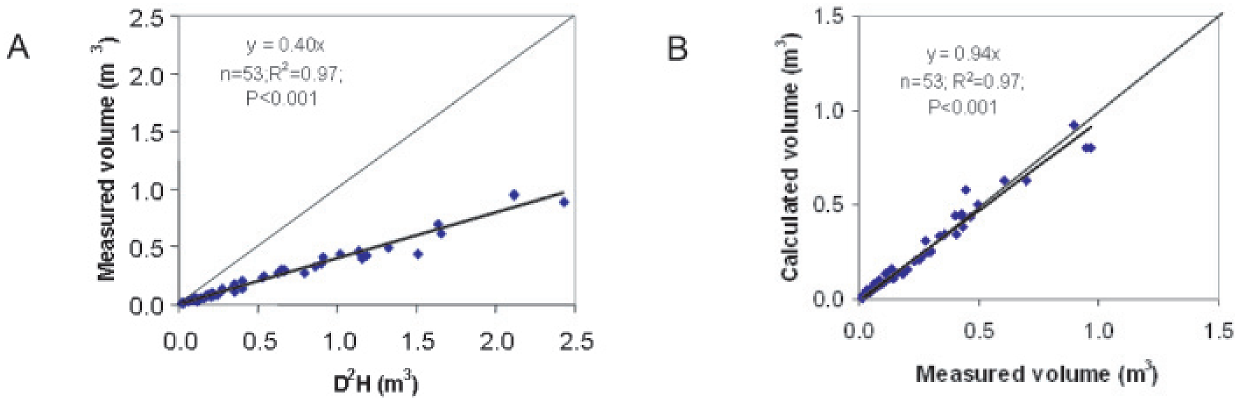

Figure 5. Tree volume versus D^2H where D is diameter at 1.30 m and H is total height (a). Tree estimated volume using equation (8) and measured tree volume. The straight line implies that generic volume table for broad-leaved species can be used also for the two species studied (b). All species together are reported.

Table IV. Coefficients of the equations in the logarithmic form of biomass (B) and diameter on 1.30 m (D) of the form: $\ln B_i = \ln a + b \ln D$. R^2, s.e. and SEE denote respectively the coefficient of determination, the standard error for the coefficients a and b and the standard error of the estimate for 38 (ash) and 10 (wych elm) degrees of freedom.

	Y	X	a	ln (a)	b	R^2	s.e. (ln a)	s.e. (b)	SEE
Ash	$\ln B_s$	ln D	0.07	–2.69	2.76	0.97	0.09	0.03	0.23
	$\ln B_t$	ln D	0.01	–4.75	2.14	0.77	0.13	0.05	0.47
	$\ln B_l$	ln D	0.005	–5.40	2.14	0.77	0.13	0.05	0.47
	ln B	ln D	0.08	–2.54	2.72	0.97	0.09	0.03	0.22
Wych elm	$\ln B_s$	ln D	0.03	–3.46	2.93	0.99	0.55	0.10	0.21
	$\ln B_t$	ln D	0.48	–0.74	1.00	0.94	0.51	0.09	0.17
	$\ln B_l$	ln D	0.18	–1.69	1.00	0.94	0.51	0.09	0.17
	ln B	ln D	0.08	–2.51	2.63	1.00	0.44	0.08	0.13

B_S: stem and branches biomass; B_t: twigs biomass; B_l: leaves biomass; B: total biomass

Table V. Coefficients of the equations of the form: $B_i = a\, D^b$ where B_i is tree compartment biomass and D is diameter at 1.30 m. Symbols are the same of Table IV. SS is the sum of squares for error in arithmetic unit. In this case a and b and the coefficient of determination (R^2) were calculated using a nonlinear interpolation (see test for more details).

	Y	X	n. obs.	a	b	R^2	s.e.		SS
							a	b	
Ash	B_s	D	40	0.16	2.47	0.97	0.630	0.130	1592941
	B_t	D	40	0.01	2.31	0.85	0.006	0.300	1005
	B_l	D	40	0.003	2.31	0.85	0.003	0.300	272
	B	D	40	0.17	2.46	0.97	0.067	0.129	1709366
Wych elm	B_s	D	12	0.10	2.56	0.97	0.094	0.290	680821
	B_t	D	12	0.34	1.12	0.98	0.114	0.107	812
	B_l	D	12	0.13	1.12	0.98	0.044	0.107	120
	B	D	12	0.13	2.49	0.98	0.113	0.261	740401

As expected, the value of total above ground biomass can be measured more precisely at low than at high value of diameter (Fig. 2; $P < 0.05$). The power model ($B = aD^b$) is appropriate because the relationship between the logarithmically transformed diameter at breast height and total above-ground biomass is linear but the use of log-transformed equation causes

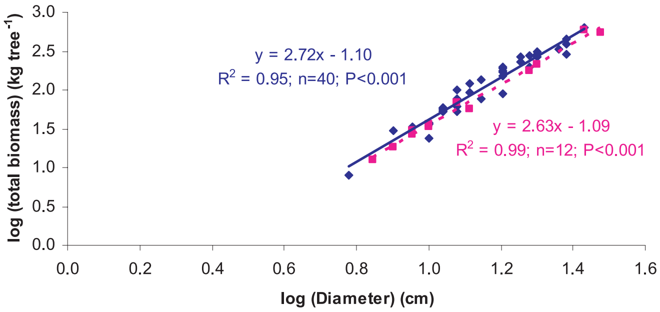

Figure 6. Logarithmically transformed diameter versus aboveground biomass for the 52 sample trees. The straight lines imply that the power model ($B = aD^b$) is appropriate.

an over-estimation of the biomass [13, 18]. Anyway, the log-transform equation is useful to test differences among species also because a lot of authors used this procedure to elaborate allometric equations. The parameters a and b estimated with this procedure for *Fraxinus excelsior* and *Ulmus glabra* (Tab. IV) are similar to those reported by Ter-Mikaelian and Korzukhin [17] for *Fraxinus americana* (white ash) (a = 0.16 and b = 2.34) and for *Ulmus americana* (a = 0.082 and b = 2.46).

Leaf area index is lower than values reported by Kimmins [10] probably because of the high density of the stand and because of close (mean diameter 4 ± 2 m) and narrow crowns (34 ± 14% of total height).

The equations found could be an useful tool for studies about either carbon stocks or productivity in these secondary succession forests.

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