Research paper

Aboveground tree additive biomass models in Ecuadorian highland agroforestry systems

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ABSTRACT

Agroforestry land-use systems in the Andean region have great socioeconomical and biophysical relevance due to the abundance of products and services they provide. Biomass estimation in these systems constitutes a priority concern as it facilitates assessment of carbon sink potential and functionality for biomass production. In this paper, a set of equations were fitted to enable easy and reliable estimation of the total aboveground biomass of four frequently used species in Andean agroforestry systems: *Acacia melanoxylon* L., *Alnus acuminata* Kunth., *Buddleja coriacea* Remy. and *Polylepis racemosa* Ruiz&Pav. The best models for each biomass component (stem, thick branches, thin branches and leaves) per species were fitted simultaneously according to SUR methodology (*seemingly unrelated regressions*). All models showed high goodness of fit statistics and more than 70% of the observed variation in biomass components was explained by the independent variables. The inclusion of height as a predictive variable in the models improved their predictive reliability and expanded the application range. The models developed here are useful for assessing the sustainability of agroforestry systems and could support governmental or non-governmental forest conservation incentive programs and initiatives.

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1. Introduction

In the Andean region, agroforestry strategy integrates production and conservation in order to diversify products and services, optimize resources and reduce risks. It generates income, ensures food security and favors the preservation of biodiversity [1,2]. Numerous initiatives to promote soil conservation and agricultural sustainability on steeply sloping lands have been implemented by governmental and non-governmental institutions in the Andean region. They mainly focus on wood productivity, natural resource management (biodiversity, watershed management and soil conservation) or multiple land use through agroforestry systems (AFS) [3]. However, the lack of basic research and an appropriate approach to the biophysical and socio-economic circumstances of farmers continues to undermine technical proposals [3,4]. There is

a clear need for more complete knowledge regarding structural and functional interactions among AFS components.

Sustainability assessment through indicators that quantify the magnitude of the positive or negative effects of AFS has been successfully implemented in the region [5]. A set of sustainability indicators related to the resource base, the function of the system itself and its impact on other systems has made possible to evaluate whether a given system is sustainable or not [6]. In this framework, priority is given to developing efficient methods for estimating biomass and carbon (C) indicators that are easily applicable across AFS, in order to evaluate carbon sink potential and improve functional analysis.

Carbon is quantified in the tree biomass of forest ecosystems by estimating the total amount of living material. Allometric equations can relate biomass to easily-measured tree level variables such as diameter at breast height (*dbh*) and total height (*ht*). On a local or site scale, this is the most practical option for assessing aboveground biomass (*AGB*) from inventory data.

Some data for *AGB* and components are available from allometric equations previously developed for Andean species [7—9].

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However, most of these species and components models were fitted independently without considering the inherent relation among the measured components and total tree biomass. Consequently, the estimates are less accurate and do not reflect the additive relationship among the component equations [10,11]. This lack of additivity means that the sum of predicted values from biomass models of tree components does not match the value obtained from models predicting the total *AGB* of the tree [12].

The aim of this study was to fit a set of equations that will easily and reliably estimate the *AGB* of four Andean species frequently used in AFS in the Ecuadorian highlands. Two tree species (*Acacia melanoxylon* R. Br and *Alnus acuminata* Kunth) and two medium-sized trees (*Buddleja coriacea* J. Rémy. and *Polylepis racemosa* Ruiz & Pav.) were studied. Implicit to the process was the incorporation of a method that would guarantee the additivity property among total tree biomass and tree component biomass estimates. This study was expected to provide an efficient tool for better biomass and C quantification, in order to improve sustainability assessment in agroforestry and forest management systems.

2. Materials and methods

2.1. Study area and sites

The study area consisted of two sites (S1 and S2, described below) located in an altitude above 3000 m on the western slopes of the north and central Ecuadorian Andes mountains (Fig. 1) and classified by their vegetation as Evergreen High Montane Forest [13]. The climate is classified as pluvial [14] typical from the Andean highlands. The annual precipitation in the study sites is 800 mm and 1400 mm in S1 and S2 respectively and a mean annual temperature around 12 °C.

The study sites involved two AFS that were established by the National Institute of Agricultural Research (INIAP) as experimental and teaching units of the National Forestry Program. Soils at both sites are classified as andosols derived from volcanic ash on well-drained, deep, fertile and short slopes [15]. The first AFS site (S1) was established in 1994 by cultivating annual crops and pastures between double-row windbreaks. Tree rows were aligned north-south in order to assess the shadow effect. Two tree combinations were tested in the windbreaks (*Acacia melanoxylon* with *Buddleja incana* Ruiz & Pav. and *Alnus acuminata* with *Spartium junceum* L.), planted alternately at 2 × 1 m spacing.

The second AFS site (S2) is a silvopastoral system established in 2002. It features a combination of three medium-sized trees (*Buddleja incana*, *Buddleja coriacea* and *Polylepis racemosa*) at 5 × 5 m spacing for low stand density. A crop rotation system with potato, bean and an oat-vetch mixture (*Avena sativa* L. − *Vicia villosa* Roth) was implemented for the first four years until a mixed pasture of perennial and annual grasses was established. Both systems were designed as research plots to evaluate alternative land-use practices and natural resource conservation for smallholder farmers [16,17].
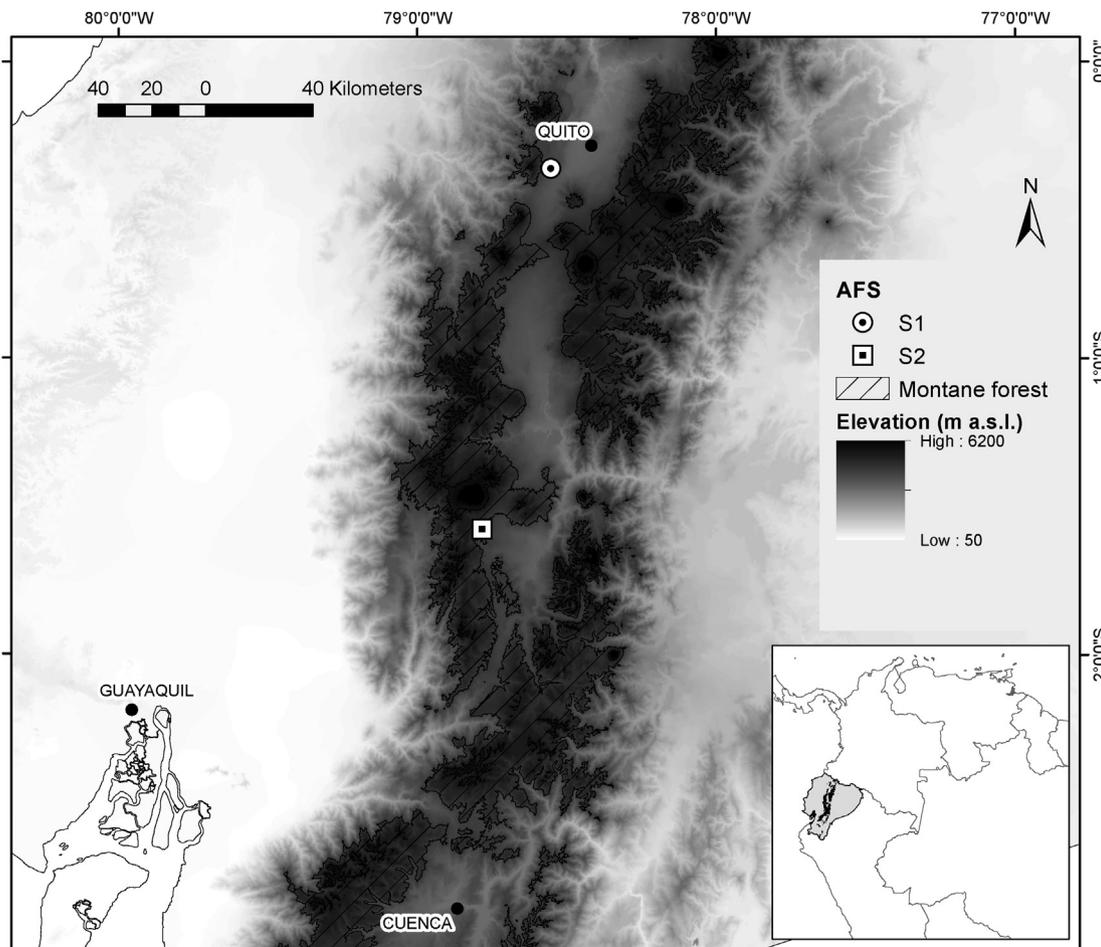

Fig. 1. Map of the study region and specific sites in the Ecuadorian Andean highlands.

2.2. Species

Four species, one exotic (*A. melanoxylon*) and three native Andean (*A. acuminata*, *P. racemosas* and *B. coriacea*) were chosen for the study. These are economically, ecologically and culturally important species that have been used extensively in agroforestry development programs [18,19]. *S. junceum* and *B. incana* were excluded due to the very small biomass dataset available.

A. melanoxylon (Fabacea) is native to the temperate forests of south-east Australia and Tasmania. This highly adaptive tree species can tolerate wide conditions of shade. It is especially interesting for its ornamental value and the quality of its dark wood [20]. In Ecuador, this species has been used in reforestation of degraded areas as it tolerates stressed conditions and grows faster than native species (though slower than pine and eucalyptus). At maturity, *A. melanoxylon* attains heights of >30 m and adapts well to montane forest above 2500 m of altitude. In spite of the recognized value of its wood, *A. melanoxylon*, does not play a significant role in the timber industry of the region [21]. However, it has been widely used for windbreak in AFS, due to its reported benefits as a nitrogen-fixing tree that can also provide forage for animals at an early tree-age [22].

A. acuminata (Betulaceae) is a relatively widespread tree species in the central and northern Andes. In Ecuador this species is found between 1200 and 3400 m of altitude [7]. *A. acuminata* trees are straight and attaining heights > 20 m at maturity with a relatively narrow and open crown. This relatively fast-growing pioneer species prefers moist site conditions and well-drained soils and has a symbiotic relationship with a nitrogen-fixing actinomycete. *A. acuminata* seeds, which are wind-dispersed, germinate rapidly; such traits enable it to swiftly colonise free spaces such as landslides and abandoned pastures [7,23]. *A. acuminata* has become a suitable species for small-to medium-scale agroforestry and reforestation programs, mainly used as wood resource for hand-crafted products and construction.

B. coriacea (Buddlejaceae) is native to the Andes mountains and grows in a wide variety of soil types, particularly from 2500 to 4250 m of altitude. This straight-stemmed, medium-sized tree can grow up to 12 m of height. *B. coriacea* as *P. racemosa*, it often branches from the base and forms a dense crown [19,24]. Although, *B. coriacea* is spread throughout the central and southern Ecuadorian Andes, it is less frequent in AFS than the other three species described [22].

P. racemosa (Rosaceae) belongs to a genus including several small-to medium-sized woody species that grow at very high altitudes (2800–4800 m) and usually form the treeline forest in this Andean region [25]. *P. racemosa* trees have irregular and gnarled stems with a multi-stemmed structure frequently observed [26]. They can reach a diameter of 40 cm and 12 m maximum height. This species grows faster than other native *Polylepis* species in the region and can reproduce by both, seed dispersal and vegetative

ramets from horizontal rooting branches. *P. racemosa* is used extensively by local highland populations in Ecuador integrated into hedgerows or silvopastures [18,19]. These species commonly serve as firewood and charcoal source due to its high calorific value (18.9–20.6 MJ kg^{-1}) [27–29].

2.3. Data

Due to the significant effort, cost and time required for a biomass harvest, the samples were taken from thinning activities in each system. Thirty *A. melanoxylon* and thirty *A. acuminata* trees were selected and sampled in 2006; and eighteen *P. racemosa* and thirteen *B. coriacea* were sampled between 2008 and 2010. The main characteristics of the trees are shown in Table 1. Diameter at breast height (*dbh*) in *A. melanoxylon and A. acuminata* and diameter at 30 cm above the ground (*d*) in *P. racemosa* and *B. coriacea* were measured using a diameter tape (cm). Total height (*ht*) was recorded using a clinometer (m) and additional height measurements of harvested trees were taken after felling.

In all cases, the destructive method was used to separate the selected trees into their biomass components. *A. melanoxylon* and *A. acuminata* trees were sampled by complete harvest method [30,31] and individuals were selected to represent the diameter classes (*dbh* or *d*). The tree biomass components considered in the field sampling were stem with bark (W_S, diameter > 7 cm), thick branches (W_{TB}, 2 > diameter > 7 cm), thin branches (W_{tb}, diameter < 2 cm) and leaves (W_l). Each component per species was weighed in the field to obtain total fresh weight. Wood disks (3–5 cm thick) including bark were cut from each tree stem at regular intervals. These disks, together with representative composite samples of components were used to determine dry matter (dry at 75 °C up to constant weight).

Because the restriction to fell complete trees of *B. coriacea* and *P. racemosa* a partial-harvest method was necessary. An alternative method to estimate biomass in multi-stemmed trees treat each stem as a separate tree [32], with this approach it is possible to obtain robust allometric relationships between stem (or main branch) diameter and the *AGB* of multi-stemmed trees [32–34]. These species produce multiple stems arising close to the ground from a single base and branching from below *dbh*. The destructively sampled stems were selected randomly from each tree, one stem was sampled per one tree and occasionally two stems of different dimensions were taken from identical trees. The stems were then cut and divided into biomass components, stem and thick branches were joined in a single woody component (W_{ST}, diameter > 2 cm), the rest of the total stem biomass represented thin branches (W_{tb}, diameter < 2 cm) and leaves (W_l), subsamples of each component were then taken for the determination of dry matter as above mentioned.

Despite the relatively small number of samples in some species, which might lead to inherently unstable estimates of the regression

Table 1
Sample size and range of diameter, total height and aboveground biomass of sampled trees.

Species	n	Diameter (cm)[a]		ht (m)		AGB (kg)[b]	
		Mean (sd)	Range	Mean (sd)	Range	Mean (sd)	Range
A. melanoxylon	30	22.4 (4.4)	13.4–31.5	17.9 (2.4)	11.3–24.3	286.8 (137.3)	69.9–612.4
A. acuminata	30	14.5 (3.2)	9.3–20.3	10.7 (1.4)	6.8–12.8	71.1 (37.8)	19.9–152.2
B. coriacea	13	11.1 (2.2)	8.6–15.6	4.2 (0.6)	3.1–5.1	13.8 (7.6)	2.9–30.4
P. racemosa	18	9.2 (3.4)	5.7–15.9	5.0 (1.2)	3.9–7.7	13.1 (16.2)	2.7–51.9

n: number of samples.

[a] Diameter: dbh for *A. melanoxylon* and *A. acuminatea*; and d (diameter at 30 cm above ground) for *B. coriacea* and *P. racemosa*; ht: total height; sd: standard deviation; range: minimum and maximum values.

[b] AGB: total aboveground biomass, in multi-stemmed species (*B. coriacea* and *P. racemosa*) represent values given for one stem.

parameters [35,36], in this study this could be tolerated due to the narrow diameter range of the medium-sized trees in AFS (Table 1) and because the full range of tree size were sampled with at least three trees for every 2.5 cm diameter class [30].

2.4. Fitting biomass equations

An initial exploratory graphical analysis was carried out to assess the relationships between the explanatory variables (*dbh*, *d* and *ht*) and the dependent variables, in order to identify outliers that might alter the modelling results. Pearson's correlations between *AGB* and dendrometric variables were then calculated.

Thirteen linear and non-linear allometric equations were tested to predict biomass contents of each component (Table 2). The equations included diameter (*dbh* or *d*) and *ht* as independent variables, based on their potential to produce models for large-scale applications and because explains most of the variability in observed tree biomass [37]. Only the models in which all parameters were significant at p < 0.05 were considered. For each biomass component in all species, the best model was selected according to the results of several statistics: specifically, the Akaike information criterion (AIC), the root mean squared error (RMSE), the proportion of variance explained by the model (R2).

Selected models for each biomass component were fitted simultaneously using *seemingly unrelated regressions* (SUR) in a system of biomass equations. This technique accounts for the contemporaneous correlations among the regression residuals, resulting in lower variance of the regression coefficients. It also incorporates the additivity property into the equation systems of components obtained by constraints on the parameters [10]. The convergence of the equation systems in the SUR procedure was checked by looking at the significance of all estimated parameters (p < 0.05). Additionally, the absence of multicollinearity in the fitted equation systems was analyzed by the condition number, if the largest condition index is above 30 then there are collinearity problems, also highly unbalanced sequences or gaps in the progression of the condition index is associated with collinearity [38].

A weighted regression was used to homogenize the residual variance [11]. In this analysis, each observation had to be weighted by the inverse of its variance (σ^2_i); which was estimated through a power function of an independent variable $\sigma^2_i = (X_i)^k$ or the logarithm form of the function $\ln \hat{e}^2_i = \ln \Upsilon + k \ln(X_i)$, where, $\hat{e}^2_i$ are the estimated errors of the unweighted model. The most reasonable value of the exponential term *k* was considered to provide the most homogeneous studentized residual plot [10,11]. The above system of biomass equations for each species and the weighting factor for

avoid heteroscedasticity problems $1/(X_i)^k$ was included in SUR fit using Model Procedure in the SAS/ETS [39].

Along with goodness of fit, several other parameters were measured and evaluated. The relative error of the predicted (*AGB predict*) versus measured (*AGB measured*) total aboveground biomass for each species was calculated to evaluate the overall predictive power of the equation systems (Eq. (1)) [37]. Thus, the mean relative error (%) in each species represented the overall bias of the equation system, and accuracy was determined by calculating the standard deviation of the relative error (%). Additionally, the relative error distribution along the diameter range in each species was plotted and compared.

$$\text{Relative Error} = 100 * \left(\text{AGB}_{\text{predict}} - \text{AGB}_{\text{measured}} \right) \qquad (1)$$

3. Results

The biomass proportion of stem in *A. melanoxylon* and *A. acuminata* with respect to the total *AGB* was greater than 50%, whereas W_{TB} and W_{tb} together represented more than 28% and W_l was lower than 12% in both species. The contribution of W_{ST} to the total biomass in *B. coriacea* and *P. racemosa* was 50%–75%, respectively, and W_{tb} showed the greatest variability than others components in medium-sized species (Fig. 2).

The correlation of diameter (*dbh* or *d*) with *AGB* was high (>0.93) and showed very significant values in all biomass components and species. Total height showed a slightly lower correlation with *AGB* in tree species (0.66 for *A. melanoxylon*, 0.65 for *A. acuminata*) than in medium-sized trees (0.82 for *B. coriacea*, 0.96 for *P. racemosa*). However, this relation varied within components depending on the species considered, but the stem or its combination with thick branches was higher than thin branches or leaves.

All biomass components models fitted and selected for each species explained more than 70% of the observed biomass, only W_l model for *B. coriacea* showed relative lower R^2 value (0.45). To solve this problem, this component was combined with thin branches (W_{tb+l}) resulting in a significant improvement in model performance (Appendix A.). All models included diameter (*dhh* or *d*) and *ht* as independent variables, except W_{ST} of *P. racemosa* which only included *d*. No common or general allometric model for all components and species was found. In *A. melanoxylon* the second ranked model for W_{tb} was selected due to a muticollinearity problems detected in the condition number test. For each species, a system of biomass equations was fitted by SUR methodology with the component selected models. The model parameters, goodness-of-fit (R^2) and root mean squared error (RMSE) were listed in Table 3 for each biomass equation. All parameters were significant at the 95% confidence level. All models fitted the total aboveground biomass data well with the model R^2 ranging from 0.92 to 0.97. In all species, the component models associated with crown (leaves, thick and thin branches) exhibited smaller values for the coefficient of determination than stem models (0.85–0.95).

The estimated exponent of the residual variance function (weighting factor) was shown in Table 3. The values were similar within a relatively narrow range for stem component and *AGB* in all species. However, the estimated factor showed much greater variation among the other components within species, being the greatest for leaves components in *A. melanoxylon* and *A. acuminata* and the factor associated with thin branches component in *B. coriacea* and *P. racemosa*.

The overall bias and accuracy values calculated (Eq. (1)) showed the highest overestimation of total tree biomass for *A. melanoxylon* (3.2%) and an acceptable uncertainty (16.3%). For *A. acuminata* the

Table 2
Biomass models tested for different tree components.

	Model
1	$W_i = \beta^* D^* Ht$
2	$W_i = \beta^* D^2 {}^* Ht$
3	$W_i = \beta^* D + \lambda^* D^2$
4	$W_i = \beta^* D + \lambda^* D^2 + \theta^* D^2 {}^* Ht$
5	$W_i = \beta^* D + \lambda^* Ht$
6	$W_i = \beta^* D^2 + \lambda^* D^2 {}^* Ht$
7	$W_i = \beta^* D^2 + \lambda^* Ht$
8	$W_i = \beta^* D^2 + \lambda^* Ht + \theta^* D^2 {}^* Ht$
9	$W_i = \beta^* D^2 + \lambda^* D^* Ht$
10	$W_i = \beta^* D^2 {}^* Ht + \lambda^* D^* Ht$
11	$W_i = \beta^* D^{\lambda} {}^* Ht^{\theta}$
12	$W_i = \beta^* D^{\lambda}$
13	$W_i = \beta^* (D^2 {}^* Ht)^{\lambda}$

W_i: biomass component (kg); D: diameter at breast height (cm) or diameter at 30 cm from ground (cm) depending on the species; Ht: total height (m); β, λ and θ: model parameters.
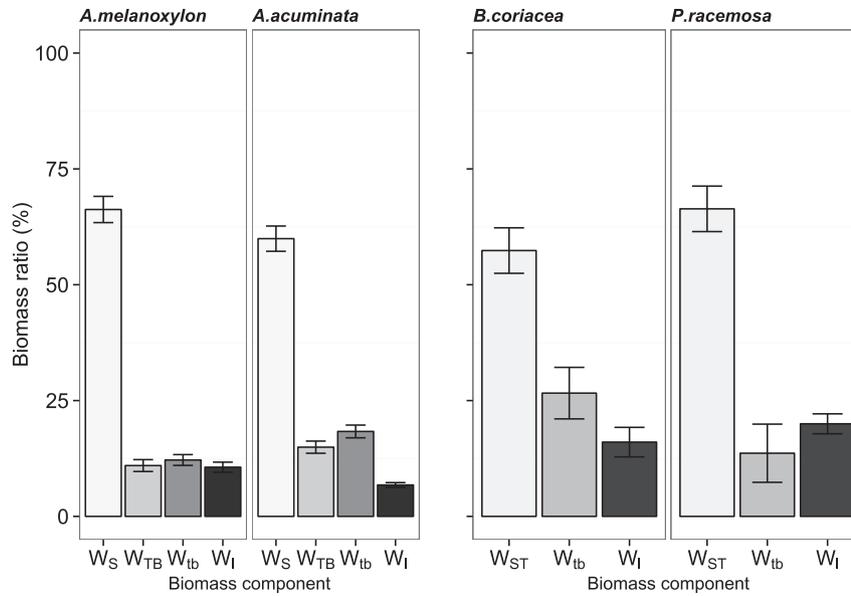
Fig. 2. Biomass ratio (Biomass component/*ABG*) in each species. Values are means and error bars ± 95% CI. (W_S, W_{TB}, W_{tb}, W_l, W_{ST} represent the stem biomass, thick branches biomass, thin branches biomass, leaves biomass and steam + thick branches biomass, respectively).

Table 3
Biomass equation systems simultaneously fitted (SUR) and goodness-of-fit statistics for studied species.

Species/component	Biomass equation	RMSE	R²	Weighting factor
A. melanoxylon				
Stem	$W_S = 0.181385{*}dbh^2 + 0.009623{*}dbh^2{*}ht$	20.70	0.935	$1/(dbh^2{*}ht)^{0.22}$
Thick branches	$W_{TB} = 0.093038{*}dbh^2 - 0.84185{*}ht$	12.17	0.715	$1/(dbh^2{*}ht)^{1.22}$
Thin branches	$W_{tb} = 0.121198{*}dbh^2 - 0.06933{*}dbh{*}ht$	11.80	0.724	$1/(dbh^2{*}ht)^{2.90}$
Leaves	$W_l = 0.081416{*}dbh^2 - 0.63368{*}ht$	9.75	0.731	$1/(dbh)^{3.56}$
AGB		40.04	0.924	$1/(dbh^2{*}ht)^{0.27}$
A. acuminata				
Stem	$W_S = 0.097332{*}dbh^2 + 0.008069{*}dbh^2{*}ht$	4.47	0.949	$1/(dbh^2{*}ht)^{0.85}$
Thick branches	$W_{TB} = 0.075098{*}dbh^2 - 0.52502{*}ht$	3.50	0.798	$1/(dbh^2{*}ht)^{2.38}$
Thin branches	$W_{tb} = 0.086093{*}dbh^2 - 0.50935{*}ht$	3.13	0.851	$1/(dbh^2{*}ht)^{1.36}$
Leaves	$W_l = 0.0345{*}dbh^2 - 0.22484{*}ht$	1.05	0.887	$1/(dbh^2{*}ht)^{4.77}$
AGB		10.03	0.937	$1/(dbh^2{*}ht)^{0.70}$
B. coriacea				
Stem + thick branches	$W_{ST} = 0.014721{*}d^2{*}ht$	1.80	0.853	$1/(dbh^2{*}ht)^{1.73}$
Thin branches + leaves	$W_{tb+l} = 0.010351{*}d^2{*}ht$	1.27	0.778	$1/(dbh^2{*}ht)^{2.00}$
AGB		0.93	0.926	$1/(dbh^2{*}ht)^{-1.47}$
P. racemosa				
Stem + thick branches	$W_{ST} = -0.31316{*}d + 0.107353{*}d^2$	1.79	0.946	$1/(dbh^2{*}ht)^{0.98}$
Thin branches	$W_{tb} = -0.09796{*}d^2 + 0.023228{*}d^2{*}ht$	2.73	0.862	$1/(dbh^2{*}ht)^{2.21}$
Leaves	$W_l = 0.00358{*}d^2{*}ht$	0.61	0.891	$1/(dbh^2{*}ht)^{0.81}$
AGB		2.90	0.971	

W_S, W_{TB}, W_{tb}, W_l, W_{ST} W_{tb+l} represent the stem biomass, thick branches biomass, thin branches biomass, leaves biomass, steam + thick branches biomass and, thin branches + leaves biomass, respectively (kg). AGB: total aboveground biomass, in multi-stemmed species (*B. coriacea* and *P. racemosa*) represent values given for one stem; ht: total height (m); dbh: diameter at breast height (cm); d: diameter at 30 cm from ground (cm); RMSE: root mean square error; R²: coefficient of determination. *Weighting factor: (k) factor used in the power function to correct heteroscedasticity.*

total biomass model slightly over-predicted the total tree biomass (0.61%) and had the lowest uncertainty (11.9%). Both medium-sized species showed the lowest prediction error of *AGB* underpredicted −0.36% and −0.15% for *B. coriacea* and *P. racemosa*, respectively. However, while the accuracy of *B. coriacea* (14.1%) was similar than tree species *P. racemosa* had the greatest uncertainty (31.7%).

Additionally, we analyzed the magnitude of error variation and applicability of the final equation systems using the error distribution in relation to the relative diameter (Fig. 3). In all species, the mean relative error of the estimations increased in the distribution tails but decreased to under 15% in the second and third quartile.

4. Discussion

Available estimates of biomass and C in agroforestry have become important for evaluating AFS potential in climate change mitigation and adaptation strategies. The set of equations obtained in this study for four species (*A. melanoxylon*, *A. acuminata*, *B. coriacea* and *P. racemosa*) provide an operational method for obtaining accurate *AGB* estimates in Ecuadorian highland AFS.

Biomass additivity has been recognised as a desirable characteristic of a system of equations for predicting component as well as total tree biomass [12,31]. The use of the seemingly unrelated regressions (SUR) method to fit the system of equations guarantees
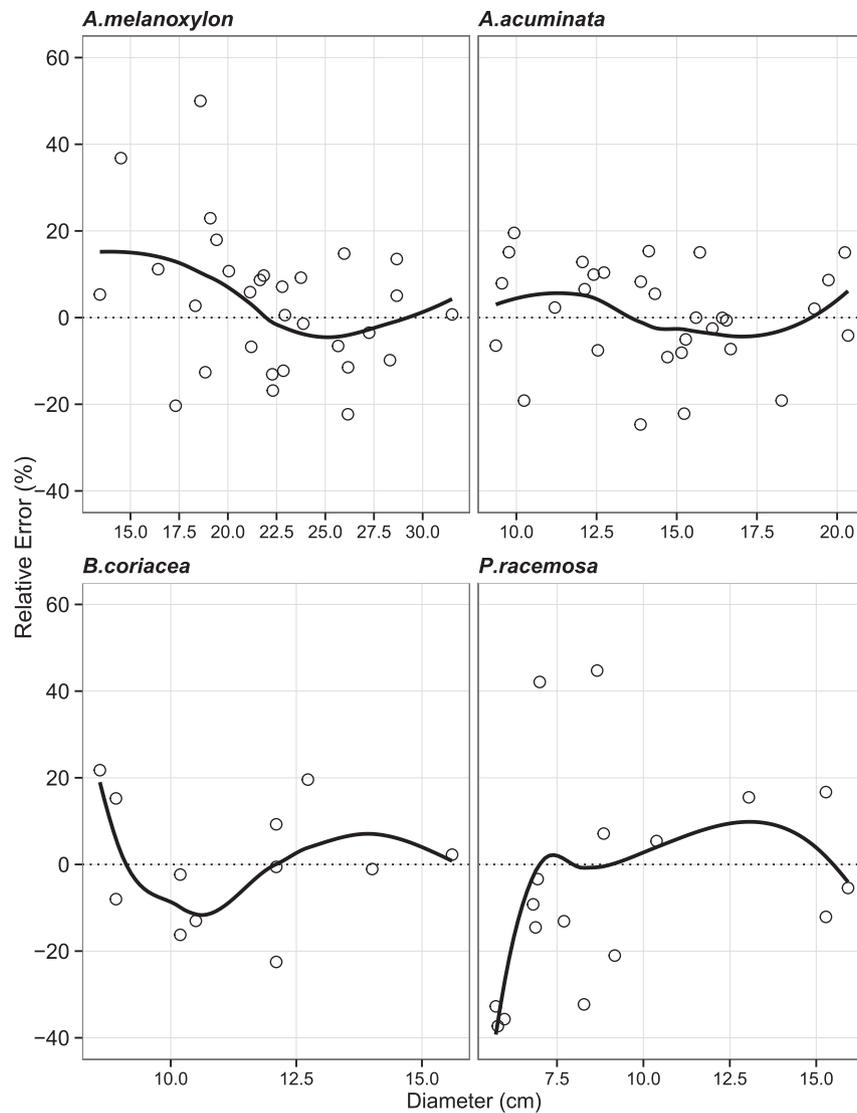
Fig. 3. Relative error in AGB predictions based on stem diameter for the species studied (*dbh* for *A. melanoxylon* and *A. acuminata* and *d* for *B. coriacea* and *P. racemosa*). Solid lines are smoothed errors using a lowess method.

this property and reducing the confidence and prediction intervals of the biomass estimations [10] and using the power function to directly fit the original biomass data scale can also provide model fitting as well as the log-transformed models [12,40]. Furthermore, our results in Table 3 showed high goodness of fit in all components and species equation systems fitted with SUR methodology. However, the use of the models outside their range of validity is not recommended because the allometric relationships are not constant and can change in different ways according to species, size and age [37,41]. Biomass prediction based on a constant allometry increases accuracy errors and uncertainly in estimations.

The ability to predict the biomass of large woody components such as stems and total *AGB* tends to be more stable than that of crown components such as branches and leaves. In all models, coefficients related only to the diameter (*dbh* or *d*) were positive for components and *AGB*. In contrast, coefficients were negative in most models that included *ht* or both independent variables, especially for the crown components in *A. melanoxylon* and *A. acuminata*. This indicates that in crown components the biomass increases with increasing diameter, and the negative sign associated with total height can be interpreted as an indirect expression

of the competitive environment of the tree, which involves interactions between species shade tolerance and stand/site attributes [40]. The same relationship among biomass components and explanatory variables has been observed for these species in forest stands [7,42,43]. Height and diameter are common, easily-measurable variables in AFS [1,41] and inclusion of both in the models enhances their predictive reliability and expands their potential for application to different sites [44,45].

The differences in proportional biomass distribution among components reflect morphological and ecological species traits. However branch and foliage biomass are naturally more variable than woody components (Fig. 2) since they are influenced to a greater extent by factor internal to stands growth such as stand density and competition status, and by external factors such as climate condition or disturbing factors (herbivory, wind or fire damage) [12,41]. Similar biomass partitioning within crown components in *A. melanoxylon* are related with diamond-shaped crowns in the trees sampled [20]. *A. acuminata* is a semi-deciduous species, so the lowest proportion of leaves biomass among tree species was expected, however an adequate fit in the foliar biomass model was obtained. Biomass of thin branches and

leaves were combined in the medium-sized trees to deal with their high variability, the model included in the SUR equations system solves the problem and maintains the applicability approach because both components share the same practical use.

In the AFS studied, the greater biomass variability in the components thin branches and leaves, especially observed in *B. coriacea* and *P. racemosa*, can be explained by two main disturbing factors: herbivory and harvest for firewood [18,29]. In the case of grazing, a heavy intensity strongly affected height-growth and seedling survival in silvopastoral systems with *Polylepis* species [46]. Although, amount of firewood extracted from trees in AFS was not quantified, it is expected to have a significant impact in biomass proportions considering the recurrent use of native tree-species stands as firewood source by Andean population [29,47,48]. Consequently, the management intensity can modify crown geometry and therefore the heterogeneity of branch and leaf biomass from tree to tree.

Despite estimation errors derived from species-specific allometric models based on a small number of samples [36], the applicability of these equations systems needs to be restricted with some considerations. The allometric relationships were only observed within the range of values used to fit the models, which represents just a section of the ontogeny of these species (Table 1). Our models tend to slightly biased the *AGB* estimates by −0.36–3.2% among species, however the models bias as a function of diameter (*dbh* or *d*) were lower in second and third quartiles with the highest numbers of individuals in all species (Fig. 3). The models can be applied more efficiently inside these respective-species diameter classes due to the higher bias in the smallest or largest trees.

Constructing species-specific allometric models for the structural and compositional diversity of AFS in Andean ecosystems is a complex, destructive, time-consuming and expensive task, and for some purposes, such as regional estimates of biomass, the application of allometric biomass models based on regional or pantropical compilations should be preferred to site or species-specific models [36,49]. However, considering the variability found in allocation of biomass component equations among the studied species in our research, obtaining a system of equations for each species was essential to accurately estimate biomass per component and *AGB* of the tree. These component-specific estimates are relevant because they are required to evaluate the positive or negative effects of trees on AFS into a sustainability assessment [6,29] through functional indicators such as nutrient stocks and cycle, biomass and carbon allocation, availability of firewood and interactions within others AFS components, considering different management options and intercropping arrangements [23,50–52].

In the last decades, the area under AFS management has been increasing steadily in the region [53] due to national, regional, governmental and non-governmental forest conservation incentive programs for enhancing land-use sustainability [3,19]. The additive biomass models in this study can be easily applied for assessing different AFS sustainability approaches, which is an activity that requires a useful tool for estimating biomass as an indicator of the ecological traits of woody species. Additionally, an adequate valuation of the potential uses and benefits of native tree species is also especially relevant to developing conservation strategies and promoting the use of native woody species in traditional AFS.

5. Conclusions

Our allometric models, based on seemingly unrelated regressions (SUR) methodology, can provide accurate biomass estimations that guarantee additivity among biomass components for *Acacia melanoxylon*, *Alnus acuminata*, *Buddleja coriacea* and *Polylepis racemosa* in Ecuadorian highland AFS. Additionally, the structural characteristics of the models improve their predictive reliability and expand the application range by including diameter and height as explanatory variables. This contributes to better explain biomass variability according to stand/site attributes and competitive conditions.

The availability of components biomass estimates are especially relevant to developing management practices and conservation strategies in medium-sized species, which wood production is not the main function in AFS.

The models developed here can be implemented in programs and initiatives that require a simple and efficient method for measuring biomass and C production. This makes it possible to evaluate biomass dynamics as sustainability indicators in different land-use systems. It can also contribute to inform about the provision of ecosystem services through AFS for community incentives.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2015.05.026.

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