ALLOMETRIC MODELS TO ESTIMATE ABOVEGROUND BIOMASS OF SMALL TREES IN WET TROPICAL FORESTS OF COLOMBIAN PACIFIC AREA[1]

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ABSTRACT – World wet tropical forests, and especially the ones in the Colombian Pacific area, are the target of a small tree (minor diameter) selective harvest process, used in short-cycle industries, such as bioenergy. This situation generates a reduction in stored carbon and biomass, and becomes an emission of greenhouse gases (GHG). Allometric models for aboveground biomass are few, despite being an important tool of carbon calculation. The goal of this study was to develop multi-species allometric models for small trees aboveground biomass in wet tropical forests. A total of 61 individuals (diameter at breast height -DBH- < 12 cm) was measured, cut and weighed to estimate their biomass. The model with the best adjustment was selected considering criteria of determination coefficient (R^2) and adjusted R^2, mean quadratic error of prediction, Akaike and Bayesian Information Criteria and the biological logic of the model. Best-fit allometric model (R^2 = 0,72) was with DBH and total height as independent variables, considering that it is a multi-species model coming from forests with a high diversity.

Keywords: Forest harvest; Carbon; Mitigation.

MODELOS ALOMÉTRICOS PARA ESTIMAR A BIOMASA AÉREA DE ÁRVORES PEQUENAS EM BOSQUES HÚMIDOS TROPICAIS DO PACÍFICO COLOMBIANO

RESUMO – Os bosques do trópico húmido no mundo e, especialmente os do Pacífico Colombiano, estão a ser submetidos a um aproveitamento selectivo de árvores de diâmetros menores, utilizados em indústrias de ciclos curtos, tal como a bioenergía. Esta situação gera uma redução na biomasa e o carbono alojado e constitui-se numa emissão de gases de efeito invernadero (GEI). Os modelos alométricos para a estimativa da biomasa acima do solo de árvores pequenas são escassos, apesar de ser uma importante ferramenta para o cálculo do carbono. O objectivo do estudo foi desenvolver modelos alométricos multi-espécies para estimar a biomasa acima do solo em bosques húmidos tropicais. Seleccionaram-se 61 indivíduos (diâmetro à altura do peito -DAP- < 12 cm), que eles foram medidos, cortado e pesado para estimar a sua biomassa. Seleccionou-se o modelo de melhor ajuste considerando critérios de coeficiente de determinação (R^2) e R^2 ajustado, erro quadrático médio de predição, Critérios de Akaike e Bayesiano de Informação e a lógica biológica do modelo. Alométrica modelo melhor ajuste (R^2 = 0,72) foi a DAP e altura total como variáveis independentes, considerando que é um multi-espécies de florestas com um modelo de elevada diversidade.

Palavras-Chave: Aproveitamento florestal; Carbono; Mitigação.

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1. INTRODUCTION

Forests play a specific and very important role in the global carbon-cycle, absorbing carbon dioxide during photosynthesis and storing it above and belowground (Ilyas, 2013). A mechanism of mitigation and adaptation to climate change are the projects of Reduction of Emissions from Deforestation and Forest Degradation (REDD+) as a political-effective option. One of its goals is to estimate the carbon reserves stored in the forests (Field et al, 2014). The existence of local allometric models to estimate biomass in different land uses is a fundamental part of the carbon inventories, and these are a basic requirement to develop forest projects for greenhouse gases (GHG) mitigation. Forest biomass has been studied with different purposes, among which is the nutrient cycle, for energetic purposes, in forest growth assessment, for forest management purposes, environmental impact mitigation, and obtaining economic incentives for forest preservation and the reduction of such gases (Sanquetta et al., 2014). Being aware that forest cover is the main carbon sink, these ecosystems are considered as a climatic change mitigation strategy at global level (FAO, 2010; Banco Mundial, 2018). The main threat to conservation of forests in Bajo Calima, Valle del Cauca and Colombian Pacific is the indiscriminate tree harvest of the commercial species most appreciated by the community (Programa de las Naciones Unidas para el Desarrollo [United Nations Development Program] PNUD, 2010), which has caused forest destruction and a modification in the landscape that may start biodiversity degradation (Martínez, 2007).

The Bajo Calima population, mostly of African-descending and organized into Community Councils, is searching for sustainable alternatives for their forests protection. This population, just like many others in the Colombian Pacific, due to its environmental and socio-economic characteristics, are mainly dependent on wood products such as beams, poles and posts of minor diameters that are used in mines and for their sustenance as firewood (Programa de las Naciones Unidas para el Desarrollo - PNUD, 2010). From 2013, A REDD+ project was started in Bajo Calima and Bahía Malaga with the purpose of reducing climatic change and contribute to the conservation of biodiversity, increasing sustainable development of the local communities (Verified Carbon Standard -VCS-, 2015).

Allometric models allow estimating biomass based on variables measured in forest inventories (diameter at breast height -1,3 m from ground, DBH – and total height - TH – or at canopy base - CBH) (Andrade et al., 2014). However, biomass models are specific for each type of ecosystem, life zone, species or group of species (Segura and Kanninen, 2005; Picard et al., 2012; Andrade et al., 2014). Therefore, local models are a good practice according to IPCC (2006). Allometric models by Chave et al. (2005) and Álvarez et al. (2012) comprise a good approximate to estimate aboveground biomass of tropical forests in regions where no models have been developed, since these are few or non-existent in the Colombian Pacific.

Multi-species allometric models, developed with representative species of a forest, in order to estimate biomass in individuals of minor diameters (DBH < 10 cm) are more scarce than for trees (DBH ≥ 10 cm), such as the ones developed by Álvarez et al. (2012) for Colombian natural forests and the ones by Brown et al. (1989), Chave et al. (2005) and Nelson et al., (2014) for tropical forests. A few models for minor individuals include the ones produced by Andrade et al., (2008) for saplings and seedlings (0,3 cm < DBH < 10 cm) in high fallows in the tropical zone in Talamanca, Costa Rica and by Hughes et al., (1999) for trees with DBH < 10 cm in secondary forests on wet tropics in Tuxtla, México.

The goal of this research was to develop a multi-species allometric model to estimate total aboveground biomass of minor diameter individuals (DBH < 12 cm) in forests intervened in Bajo Calima, and the Colombian Pacific.

2. MATERIALS AND METHODS

2.1. Area of study.

The research was carried out in the *Consejo Comunitario de la Cuenca del Bajo Calima* (CCCBC), more specifically in the communities of La Estrella, Las Brisas, El Crucero km 9, Villa Estela and San Isidro. CCCBC is located in the coordinates 03° 57´ 12,7´´ N and 76° 59´ 26,6´´ W, at an altitude of 50 m and at approximately 20 km from the Municipality of Buenaventura. The area of study is characterized for presenting an annual mean temperature and precipitation of 26°C and 7184 mm, respectively, a mean relative humidity of 88% and a 966 h/year of sunlight (Instituto de Hidrología, Meteorología y Estudios Ambientales [Hydrology, Meteorology and Environmental Studies Institute] –(IDEAM, 2016).

2.2. Selection of species and individuals.

The species selected for the construction of the multi-species allometric models were the ones with the highest commercial use in the zone. According to Lozano and González (2011), the major timber products obtained from these secondary forests are around woods in shapes of beams, poles, logs and posts, whose commercialization is focused mainly in small individuals (4 to 5 years old) with a DBH between 8 and 15 cm.

A total of 61 individuals were sampled, which were harvested by the communities, and belonging to 25 species and 17 families: *Protium colombianum* Cuatrec. (Burseraceae), *Calophyllum mariae* Planch. & Triana (Clusiaceae), *Mabea chocoensis* Croizat and *Tetrorchidium ochroroleucum* Cuatrec. (Euphorbiaceae), *Casearia oblongifolia* Cambess. (Saliacaceae), *Goupia glabra* Aubl. (Goupiaceae), *Humiria* sp (Humiriaceae), *Ocotea cernua* (Nees) Mez y *Ocotea* sp (Lauraceae), *Eschweilera* sp (Lecythidaceae), *Abarema* sp and *Inga chocoensis* T.S. Elias (Leguminoseae), *Pterygota excelsa* (Standl. & L.O. Williams) Kosterm; and *Sterculia pilosa* Ducke (Malvaceae), *Miconia lepidota* Schrank & Mart. ex DC. And *Miconia* sp (Melastomataceae), *Otoba lehmannii* (A.C. Sm.) A.H. Gentry and *Virola* sp (Myristicaceae), *Ogcodeia ulei* (Warb.) J.F. Macbr., *Chrysophyllum* sp and *Pouteria* sp (Sapotaceae), *Simarouba amara* Aubl. (Simaroubaceae), *Pourouma aspera* Trécul (Urticaceae), *Qualea lineata* Stafleu and *Vochysia ferruginea* Mart. (Vochysiaceae). The individuals selected were classified as seedlings (DBH < 5 cm and TH $\geq 0{,}3$ m), saplings ($5 \leq$ DBH < 10 cm) and trees ($10 \leq$ DBH < 12 cm).

2.3. Measuring and biomass estimation.

Once the sampled trees were selected and taxonomically identified, its DBH, TH and CBH were measured. The individuals were cut and separated in three components: stem, large branches (diameter > 2 cm), small branches (diameter ≤ 2 cm) and leaves, every one of each was weighed by taking two sub-samples (of approximately 250 g each) to estimate dry matter (60 ºC until constant weight). Then, total aboveground biomass (Bt) per individual, adding the biomass of all components, was estimated.

2.4. Allometric model selection.

Pearson correlation coefficient (r) between the dependent (Bt) and independent variables (DBH, TH and CBH) was calculated. Then, linear regression analysis with and without logarithm transformations were carried out. The best models were selected considering the criteria of: highest determination coefficient (R^2) and adjusted R^2, lowest mean quadratic error of prediction (ECMP), Akaike Information Criteria (AIC) and Bayesian Information Criteria (BIC) and the models biological logic (Clutter et al., 1983; Segura and Andrade, 2008; Andrade et al., 2014). Just the same, an analysis of estimated *vs* observed and residuals was carried out for the selected models.

The models with the best adjustment were compared with the ones developed in tropical wet and very wet forests of America, Asia and Oceania used for Colombia with DBH > 10 cm (Eq. 1; Chave et al., 2005) and or those for DBH < 10 cm developed in Costa Rica (Eq. 2; Andrade et al., 2008) and Mexico (Eq. 3; Hughes et al., 1999).

$$Ln(Bt) = -3{,}08 + 1{,}007*Ln(DBH^2*TH*g) \quad [Eq. 1]$$

$$Log(Bt) = -1{,}27 + 2{,}2*Log(DBH) \quad [Eq. 2]$$

$$Ln(Bt) = (4{,}94 + 1{,}06*Ln(DBH^2)*1{,}14)/1000 \quad [Eq. 3]$$

Where; Ln: natural logarithm; Log: base-10 logarithm; Bt: total aboveground biomass (kg/tree); DBH: diameter at breast height (cm); TH*:* total height (m); *g*: specific gravity of wood (g/cm^3).

Specific gravity was used per species or genus reported in the wood density global database Zanne et al. (2009); while for the rest of the species, a value of 0,6 g/cm^3, recommended by IPCC (2006) for tropical America, was used.

3. RESULTS

3.1. Features of sampled individuals.

Sampled individuals showed a DBH range from 2,0 to 12,0 cm, a TH of 3,9 to 15,3 m and a Bt that varied between 0,8 and 42,6 kg/tree. *Calophyllum mariae, Abarema* sp, *Miconia* sp and *Chrysophyllum* sp are represented in all diametric classes (Table 1), which probably explains their high natural regeneration natural and the strong harvest pressure to which are being object of. Sampled trees showed a mean Bt of 17,9 kg/tree, from which 60% was found in the stems (Table 1). In contrast, leaf biomass from the sampled trees varied between 0,1 and 10,7 kg/tree, making the 15% of the Bt (Table 1).

3.2. Correlation between variables.

Bt was best correlated with TH and DBH than with CBH (r = 0,77; r = 0,69 and r = 0,52, respectively; Figure 1). Just as expected, stem biomass was better explained by DBH than by TH or CBH (r = 0,78; r = 0,76 and r = 0,55, respectively).

3.3. Model adjustment.

The best fit multi-species models to estimate Bt are based on TH, DBH, or in the combination of these two variables (Table 2). These models turned out to be the best according to the statistics used and were logical from the biologic point of view. The best multi-species model includes the combination of TH and DBH as independent variables ($R^2 = 0,72$); meanwhile those with only one variable show adjusted R^2 for DBH and TH ($R^2 = 0,63$; $R^2 = 0,65$, respectively) (Table 2) for the sizes of the sampled trees.

Despite the models fit a variety of species in forests with a structural diversity, these equations show good adjustments ($0,63 < R^2 < 0,72$) and the estimates are relatively similar to observed biomass (Figure 2). However, AIC and BIC criteria allow verifying a good model adjustment. The comparative analysis of estimated *vs* observed biomass, along the statistics, indicate that the best-adjustment model was the one that includes DBH and TH variables (Eq. 4; Figure 2), which estimates sampled trees biomass with a higher precision than those based exclusively on one of these variables. Figure 2 shows the best-fit models in each of the independent variables separately and one with both together, whose error distribution can be detailed in the corresponding residual graphics.

Chave et al. (2005), Andrade et al. (2014) and Hughes et al. (1999) equations underestimate aboveground biomass of small-diameter trees sampled (Figure 3). In the case of the second model mentioned, estimations are far below the data observed of the sampled trees. However, first model estimates are closer to those carried out with the model of the Eq. 4, which was generated in this study.

4. DISCUSSION

Commonly, a high correlation between DBH and stem and large branches biomass is expected in established and well-formed individuals. It is not the case between DBH and leaves or small branches biomass in small individuals (DBH < 15 cm) (Segura and Andrade, 2008). This implies that the models to be developed must include TH or DBH as independent variable, depending on the size of the trees and the dependent variable (biomass components). In general, and as shown in some previous research, DBH is the variable that best correlates and predicts biomass (Brown et al., 1989; Chave et al., 2005; Segura and Kanninen, 2005). Besides, this variable is easy to measure and registers in most forestry inventories (Segura and Kanninen,

Table 1 – Dasometric and taxonomic characteristics and biomass of the sampled trees for the development of biomass models for small trees (DBH < 12 cm) in forests of the Bajo Calima, Buenaventura, Colombia.
Tabela 1 *– Características dasométricas, taxonómicas e biomasa dos indivíduos muestreados para o desenvolvimento de modelos de biomasa para árvores pequenas (DAP < 12 cm) em bosques de o Bajo Calima, Buenaventura, Colombia.*

Diametric class (cm)	# of individuals	Species	DBH (cm)	TH (m)	Bs	Bb	Bl	Bt
					kg/tree			
2,0 – 4,9	21	1, 2, 3, 4, 5, 6, 9, 11, 13, 14, 16, 20, 21, 24, 25	3,6 ± 0,1	6,3 ± 1,4	2,9 ± 0,5	1,9 ± 0,4	1,4 ± 0,3	6,3 ± 1,1
5,0 – 10,0	24	1, 2, 3, 5, 6, 10, 11, 12, 13,15, 16, 18, 19, 20, 21, 25	6,5 ± 0,1	8,7 ± 0,3	6,8 ± 1,4	4,0 ± 0,7	3,0 ± 0,6	18,8 ± 2,0
10,0 – 11,9	16	2, 8, 9, 10, 11, 14, 15, 16, 18, 20	9,7 ± 0,2	10,8 ± 0,5	20,7 ± 1,6	7,7 ± 0,9	3,0 ± 0,7	31,5 ± 1,7
Total	61	25	6,3 ± 0,3	8,4 ± 0,3	11,0 ± 1,1	4,3 ± 0,4	2,5 ± 0,3	16,7 ± 11,6

DBH: Diameter at breast height; TH: total height; Bfs: biomass of stems; Bb: biomass of branches; Bl: biomass of leaves; Bt: total aboveground biomass. Values correspond to mean ± standar error. 1: *Protium colombianum;* 2*: Calophyllum mariae;* 3*: Mabea chocoensis; 4: Tetrorchidium ochloroleucum;* 5*: Casearia oblongifolia;* 6*: Goupia glabra;* 7*: Humiria* sp*;* 8*: Ocotea cernua;* 9: *Ocotea* sp*;* 10*: Eschweilera* sp*;* 11*: Abarema* sp*;* 12: *Inga chocoensis;* 13*: Pterygota excelsa;* 14: *Sterculia pilosa;* 15: *Miconia lepidota;* 16*: Miconia* sp*;* 17*: Otoba lehmannii;* 18*: Virola* sp*;* 19*: Ogcodeia ulei;* 20*: Chrysophyllum* sp; 21*: Pouteria* sp*;* 22: *Simarouba amara;* 23*: Pourouma aspera;* 24*: Qualea lineata;* 25*: Vochysia ferruginea.*

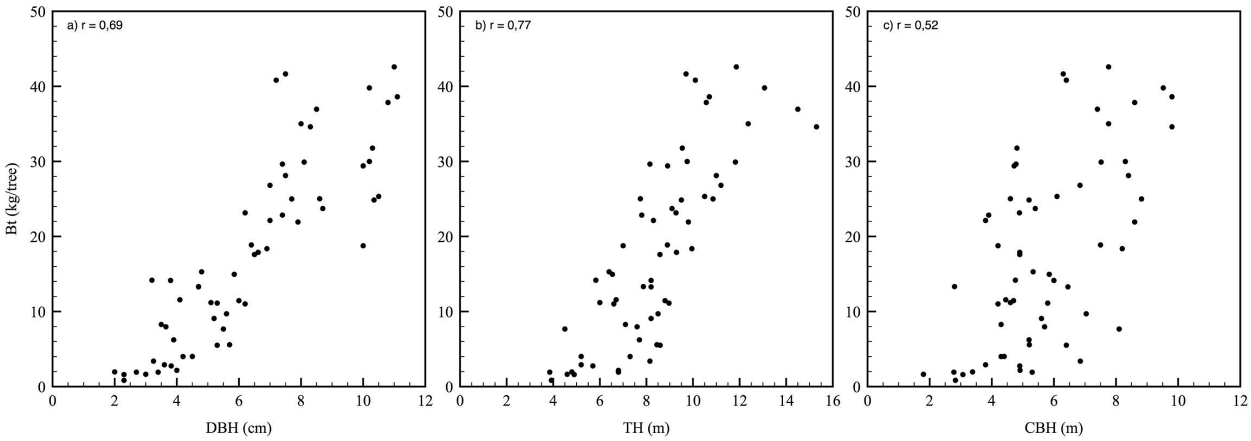

Figure 1 – Relationship between total aboveground biomass and the independent variables (a: DBH; b: TH; c: CBH) of small trees (DBH < 12 cm) in the Consejo Comunitario de la Cuenca del Bajo Calima, Buenaventura, Valle del Cauca, Colombia. DBH: diameter at breast height; TH: total height; CBH: canopy base height.

Figura 1 *– Relação entre a biomasa aérea total e as variáveis independentes (A: DAP; B: HT; C: HBC) de árvores pequenas (DAP < 12 cm) em o Consejo Comunitario de la Cuenca del Bajo Calima, Buenaventura, Valle del Cauca, Colombia.*

Table 2 – The best-fit alometric models for estimating total aboveground biomass of small trees (DBH < 12 cm) in forests of the Consejo Comunitario de la Cuenca del Bajo Calima, Buenaventura, Valle del Cauca, Colombia.

Tabela 2 *– Modelos alométricos de melhor ajuste para a estimativa da biomasa aérea total de árvores pequenas (DAP < 12 cm) em bosques de o Consejo Comunitario de la Cuenca del Bajo Calima, Buenaventura, Valle del Cauca, Colombia.*

Model	R^2	R^2 Aj	ECMP	AIC	BIC
Eq.4Ln(Bt) = -2,42 + 0,93*Ln(DBH) + 1,52*Ln(TH)	0,72	0,71	0,29	96,7	105,1
Eq.5Ln(Bt) = -0,68 + 1,74*Ln(DBH)	0,63	0,63	0,35	111,3	117,6
Eq.6Ln(Bt) = -3,02 + 2,59*Ln(TH)	0,65	0,64	0,35	109,2	115,5

Ln: natural logarithm; Bt: total aboveground biomass (kg/tree); DBH: diameter at breast height (cm); TH: total height (m); R^2: determination coefficient; R^2 Aj: adjusted R^2; ECMP: mean quadratic error of prediction; AIC: Akaike´s Information Criterion; BIC: Bayesian Information Criterion.

2005; Fonseca et al., 2009). However, in small individuals, total biomass can also be very well explained by TH, just as found on this study.

On this study, a slight improvement in the model adjustment was presented when including both independent variables (TH and DBH) than in those that have it separated. On the other hand, models involving only one of them show a higher practicality in their usage. Thus, the usage of the model that employs only TH as independent variable is more convenient, considering that it can be measured more easily in this kind of trees, consequently reducing the error. Therefore, it is possible a wider usage of the model for biomass and carbon estimation in carbon inventories and nutrient dynamics.

Many models have been developed by transforming logarithmically the dependent and independent variables, which matches these findings (Hughes et al., 1999; Chave et al., 2005; Segura and Kanninen, 2005; Andrade et al., 2008). This procedure allows linearizing data and avoiding variance heteroscedasticity, being an obvious and reasonable tool for such purposes (Mascaro et al., 2014). In the development of models, R^2 is valid as a measure of adjustment or predictive value if the model is right as much in its deterministic aspect as its random part. However, this statistic must not be the only one to be considered, given that since an adjustment could be incorrect and result in a high R^2 (Clutter et al., 1983; Sit and Poulin-Costello, 1994; Di Rienzo et al., 2009; Mascaro et al., 2011; Andrade et al., 2014).

The comparison of the model with the best adjustment of the current study with others from specialized literature permits to see its applicability, considering that some of these models are recommended as general and could be applied to the conditions of

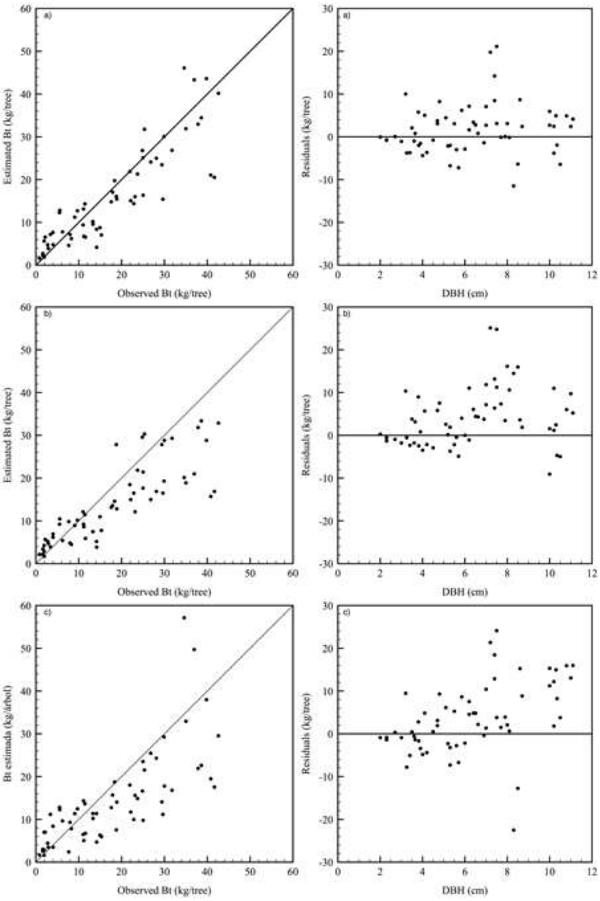

Figure 2 – Relationship between estimated and observed (measured) total aboveground biomass with the best-fit models in small trees (DBH < 12 cm) in forests of the Consejo Comunitario de la Cuenca del Bajo Calima, Buenaventura, Valle del Cauca, Colombia. Bt: total aboveground biomass; DBH: diameter at breast height. a) Eq. 4; b) Eq. 5; c) Eq. 6.

Figura 2 *– Relação entre a biomasa aérea total estimada e observada (medida) dos modelos de melhor ajuste em árvores pequenas (DAP < 12 cm) em bosques do Consejo Comunitario de la Cuenca del Bajo Calima, Buenaventura, Valle del Cauca, Colombia. Bt: biomasa aérea total; A) Ec. 4; B) Ec. 5; C) Ec. 6.*

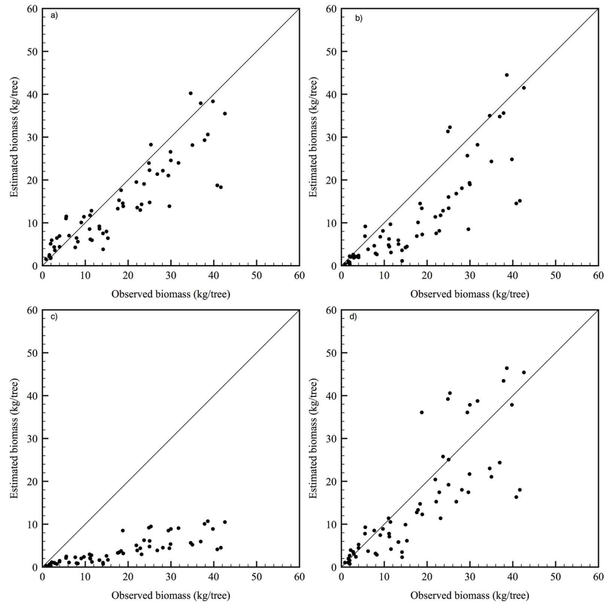

Figure 3 – Comparison between observed and estimated total aboveground biomass (Bt) in small trees (DBH < 12 cm) in forests of the Consejo Comunitario de la Cuenca del Bajo Calima, Buenaventura, Valle del Cauca, Colombia. a) This study (Eq. 4); b) Chave et al. (2005) (Eq. 1); c) Andrade et al. (2008) (Eq. 2) and d) Hughes et al. (1999) (Eq. 3).

Figura 3 *– Comparação entre a biomasa aérea total (Bt) observada e estimada em árvores pequenas (DAP < 12 cm) em bosques do Conselho Comunitário da Bacia do Baixo Calima, Buenaventura, Vale do Cauca, Colômbia. A) Este estudo (Ec. 4); B) Chave et al. (2005) (Ec. 1); C) Andrade et al. (2008) (Ec. 2) e D) Hughes et al. (1999) (Ec. 3).*

tropical wet forests of the Colombian Pacific. The development of local models to estimate aboveground biomass is a valuable tool for GHG mitigation projects (Brown et al., 1989; IPCC, 2006; Segura and Andrade, 2008), such as REDD+, since it allows improving estimations and increase carbon credits (IPCC, 2006; van Breugel et al., 2011).

The model generated on this study, for small-diameter individuals (DBH < 12 cm), complements the biomass and carbon estimations in very wet tropical forests that use models such as the ones from Chave et al. (2005) for individuals with DBH $\geq$ 12 cm. Specificity in the use of these multi-species models permits to improve reserve and carbon flux estimations of these forests that are highly diverse. Local multi-species allometric models for forests are scarcely reported, usually some are found but for big trees, just like the one by Fonseca et al. (2009), who developed it using 35 species from secondary forests in the Caribbean area of Costa Rica and the one by Segura and Kanninen (2005), which involved seven species from wet tropical forest. The model generated in this study allows estimating locally the total biomass of the minor-diameter trees in the conditions of the Bajo Calima, which is a useful tool that contributes to biomass and carbon fixation studies as option for climate change mitigation and nutrient cycling.

5. CONCLUSIONS

Dasometric variables of TH and DBH obtained a high correlation with aboveground biomass, which grated the development of allometric models with good adjustment. In the case of small trees, model based exclusively on TH show significant practical advantages in their applicability, given that the measurement of this variable has little error and is easier to perform.

The comparison of the models developed in this study to those ones found on previous scientific literature ratifies the importance of generating such tools at a local scale. Multi-species allometric models generated are an important tool in order to quantify the stock of aboveground biomass and carbon of these forests in a more reliable way and formulate strategies and projects of sustainable land use.

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