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ARTICLES

Above and belowground carbon and nutrient distribution of *Samanea saman* plantation in the Eastern Andes, Colombia

Distribución de carbono y nutrientes en la biomasa aérea y abajo del suelo de una plantación de *Samanea saman* en los Andes orientales, Colombia

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ABSTRACT

In tropical soils that are poorly fertile and degraded by agriculture, native nitrogen-fixing species have the potential to recover soil fertility and carbon stock, which contribute to climate change mitigation. This study aimed to quantify the nutrients and carbon stock of a Samanea saman plantation. The aboveground biomass was estimated directly by falling nine trees 5.8 years after planting. Soil samples were collected to quantify organic carbon content and fine root biomass - FRB (Ø < 2 mm) during the rainy period. Total aboveground biomass was 51.1 Mg ha^{-1}, which was stored mostly in the stemwood with 41%. Leaves and branches Ø < 5 cm represented 30% of the aboveground biomass, but accumulated close to 50% of nutrients, except for Ca, Fe, and Mn, which were high in the stembark. The FRB was not affected significantly by soil depth (0-15 and 15-30 cm) and the collection distance from the crown radius projection (50 and 100%), with the average being 8.5 Mg ha^{-1}. The carbon stock of the forest system up to 30 cm depth of soil was 81.7 Mg ha^{-1}. These results suggest that Samanea saman is a potential native species for the rehabilitation of degraded areas in the humid lowlands of the Colombian Andes.

Keywords: reforestation, fine roots, leguminous trees, Magdalena river basin.

RESUMEN

En suelos tropicales de baja fertilidad y degradados por agricultura, las especies nativas fijadoras de nitrógeno tienen potencial de recuperar la fertilidad del suelo y stock de carbono, lo cual contribuye a la mitigación del cambio climático. Este estudio tuvo como objetivo cuantificar el stock de nutrientes y carbono de una plantación de Samanea saman. La biomasa aérea fue cuantificada directamente por el derribo de nueve arboles a los 5,8 años de plantación. Muestras de suelo fueron colectadas para cuantificar el contenido de carbono orgánico y la biomasa de raíces finas - BRF (Ø < 2 mm) durante el periodo lluvioso. La biomasa total aérea fue de 51,1 Mg ha^{-1}, la cual fue acumulada principalmente en el fuste (madera) con 41%. Las hojas y ramas Ø < 5 cm representaron el 30% de la biomasa aérea, pero acumularon cerca del 50 % de nutrientes, excepto de Ca, Fe y Mn, que fueron altos en el fuste (corteza). La BRF no fue afectada significativamente por la profundidad de suelo (0-15 y 15-30 cm) y posición de colecta con relación al radio de copa (50 y 100%) siendo la media de 8,5 Mg ha^{-1}. El stock de carbono del sistema forestal hasta los 30 cm de profundidad del suelo fue de 81,7 Mg ha^{-1}. Estos resultados sugieren que Samanea saman es una especie nativa potencial para la rehabilitación de áreas degradadas en las tierras bajas húmedas de los Andes de Colombia.

Palabras clave: reforestación, raíces finas, leguminosas arbóreas, cuenca del rio Magdalena.

INTRODUCTION

As one of the most biodiverse and carbon-dense regions, the restoration and rehabilitation of tropical forests are fundamental for mitigation efforts of climate change derived from human activities (Hubau et al., 2020). In Colombia, forest reduction due to land-use change, mainly agricultural exploitation, is common in the subregions of lowlands in the Andean region (below 1,000 m altitude) (Rodríguez et al., 2013), one of the five biogeographical regions that divide the country. In fact, after the Amazon region, the Andean region lost the biggest forest area of the country from 2013 to 2018 with an estimation of 3,677 km^2 (González-González et al., 2021). Land degradation is widespread with over 40% of Colombia's land classified as degraded (MADS, 2019). Among the 10.3 million hectares of land degraded by agricultural activities that have the potential for ecological recovery, the Andean region accounts for the largest portion, covering 6.6 million hectares (Sylvester et al., 2020).

One of the techniques for carbon sequestration is the reforestation of native trees that fix atmospheric nitrogen, especially Fabaceae trees, because they increase the productivity in regions with acid-poor soils or degraded by agriculture, as several studies have shown (Arias et al., 2011; Mosquera et al., 2012; Ragula & Chandra 2020; Zhang et al., 2022; Fonseca et al., 2023, Delarmelina et al., 2023). The average amount of living aboveground biomass of all forests in Colombia was estimated at 226.9 ± 4.5 Mg ha^{-1} (Phillips et al., 2016). Although areas degraded by agriculture could be restored with native species, given the high biodiversity of the ecosystems, local studies need to be carried out.

The biomass estimation can be done by allometric equations or tree fall (Schetinni et al., 2022). Modeling the growth and biomass forest using allometric equations facilitates monitoring and management. This reduces costly forest inventory expenses in the field, improves forest management decision-making, and carbon sequestration estimates, the latter being important in the carbon credit market (Onyekwelu et al., 2016; Duque et al., 2017). In other words, it helps predict the productivity of the plantation and the profitability of the project (Santos et al., 2017; Delarmelina et al., 2023). However, when the fall of the tree is chosen (destructive sampling), the knowledge of the nutrient distribution pattern in the tree components is useful for the sustainable management of plantations. Although it is not visible, around 60% or more of the carbon of forest ecosystems is found belowground biomass (Ehrenbergerová et al., 2016; Dantas et al., 2021; Bello et al., 2021). The fine roots' biomass and distribution are determined by the ecological conditions and intrinsic attributes of the species, even though they also show a wide plasticity in response to edaphic and weather conditions (Zhang et al., 2021; Bello et al., 2021).

Samanea saman (Jacq) Merril (Fam: Fabaceae) commonly known as rain tree is a fast-growing multipurpose tree with a natural occurrence in the Neotropical dry forest from southern Mexico to Colombia and Venezuela (Vinodhini & Rajeswari 2018). This N_2 fixing Fabaceae tree is widely used in forest restoration projects of the tropic because it tolerates acid soils and high content of Al^{+3}, even in waterlogging conditions (Vinodhini & Rajeswari 2018; Abaurre et al., 2020). It was the second most abundant species used for shade and forage, both in pasture and silvopastoral systems, in the dry savannas of the Caribbean region of Colombia (Lombo et al., 2023). Reforestation, therefore, has the potential to reverse ecosystem degradation by improving soil conditions and increasing both aboveground and belowground carbon stocks, which can help reduce erosive processes, particularly in mountainous landscapes (Mosquera et al., 2012; Van Bich et al., 2018; Olaya-Montes et al., 2021; Pabón et al., 2023).

The possible implications of promoting commercial reforestation with *S. saman* regarding the nutrient cycle and above and belowground carbon stock as an ecosystem service are unknown. In this context, the objectives of our study were: 1) to estimate the biomass and nutrient content in the different aboveground components, 2) to estimate the carbon stock in three compartments of the forestry system (aboveground biomass, fine roots Ø < 2 mm and soil) and 3) evaluate modeling in height and biomass aboveground for a young plantation of *S. saman.* This research aims to enhance the accuracy of both direct and indirect estimates of biomass and carbon in *S. saman*, contributing to sustainable plantation management.

METHODS

Area of study. The experimental area is part of the Salamaga River basin, which belongs to the larger basin of Magdalena River in the Santandereana Mountain subregion (Andean region). It is located in the La Suiza research center of Corporación Colombiana de Investigación Agropecuaria (Agrosavia), municipality of Rionegro, Santander, Colombia (550 m a.s.l.; Figure 1).

The soil is characterized by a moderate to shallow mountainous landscape and low natural fertility classified in Inceptisol and Entisol orders (IGAC 2003). Due to its mountainous relief, about 90% of the area of the subbasin is suitable for protection and conservation (Abimelec et al., 2009). The climate is tropical equatorial (Af) according to Köppen-Geiger (1936), with no definite dry season (at least one month = below 60 mm), but normally there are two less rainy periods in the year. The historical annual averages (1984-2013) of rainfall are 1,999 mm and 27.8 °C. During the study period (2014-2020) the average rainfall was 1,859 mm year^{-1} (IDEAM 2023; Figure 2). The experimental area had been a sugarcane plantation for several decades, and in the mid 90's it was divided into an agroforestry system of cacao tree (*Theobroma cacao* L.)*,* and in the flattest parts pastures for livestock. In 2009, the totality of the area was abandoned, which led to natural regeneration.

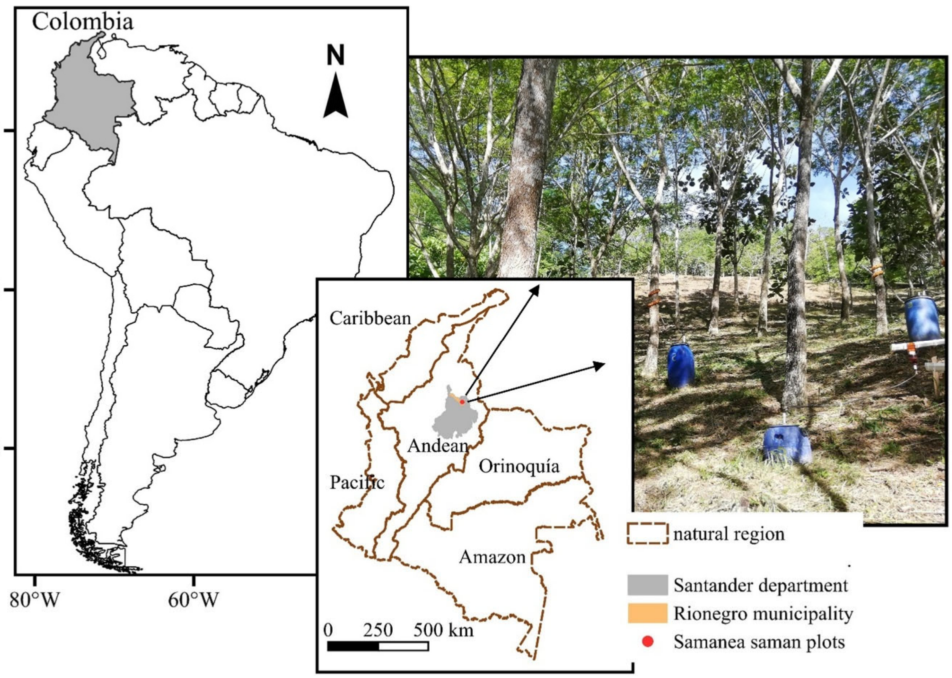

Figure 1. Location of the study area and experimental plots of *S. saman* at 5.8 years of plantation. Rionegro, Santander (Colombia).

Localización del área de estudio y parcelas experimentales de *S. saman* a los 5,8 años de plantación. Rionegro, Santander (Colombia).

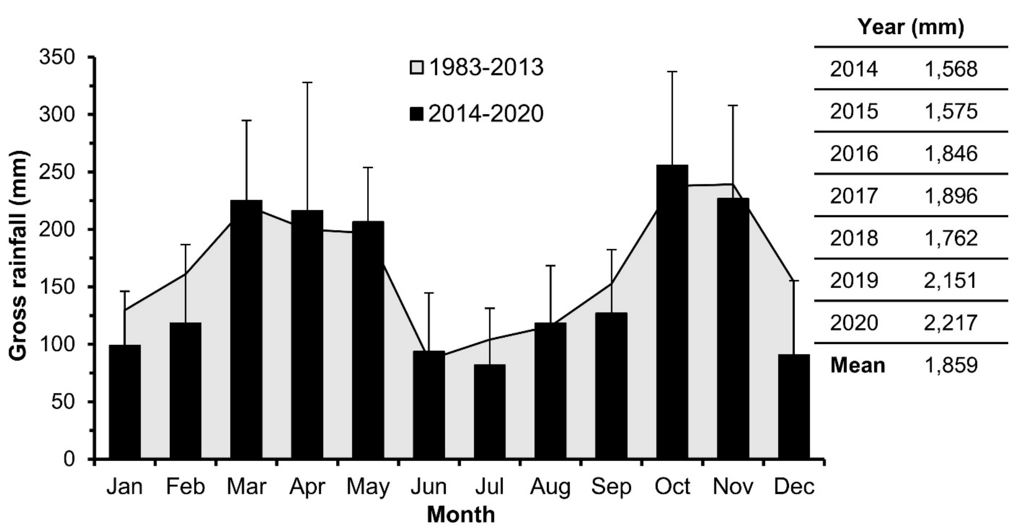

Figure 2. Monthly averages of gross rainfall during the experimental period (2014-2020) and historical period (1984-2013). Rionegro, Santander (Colombia).

Medias mensuales de la precipitación durante el periodo experimental (2014-2020) e histórico (1984-2013). Rionegro, Santander (Colombia).

The topographic survey revealed a mountain landscape with an average slope of 30% and maximum slopes of 67%.

Establishment of the experiment. The monoculture plantation of *S. saman* native from commercial seeds was established with six months old seedlings in September 2014 and it had a plant density of 5 m x 5 m (400 tree ha^{-1}). The reforestation area occupies three rectangular plots separated at 400-600 m, each of 1,000 m^2 and with 35 to 38 trees (Figure 1). A composed sample (three subsample per plot) of soil collected at 0-40 depth revealed a strongly acidic soil with low cation exchange capacity and phosphorus content with the presence of exchangeable aluminum (Table 1). To correct the soil pH, 300 g hole^{-1} of dolomitic

Table 1. Chemical and physical analysis of soil according to soil depth (D) in *Samanea saman* before (0 year) and 5.8 years after planting. Rionegro, Santander (Colombia).

Análisis químico y físico de suelo según la profundidad de suelo (D) en *Samanea saman* antes (0 años) y a los 5,8 años de la plantación**.** Rionegro, Santander (Colombia).

Time		pH(1)	C(2)	O.M(3)	P(4)	S(5)	Fe^{+3}(6)	Cu(6)	Mn(6)	Zn(6)	Al^{+3}(7)	K^{+1}(8)	Ca^{+2}(8)	Mg^{+2}(8)	CEC(9)	Bd(10)
(year)	D (cm)	H_20	g kg^{-1}				mg kg^{-1}						cmol$_c$ kg^{-1}			g cm^{-3}
0	0-40	4.50	-	-	3.60	2.67	213	2.45	9.30	1.55	1.29	0.11	2.47	0.78	3.42	-
5.8	0-15	5.67	19.1	29.5	13.6	2.03	79.2	1.43	15.6	< 1.0	-	0.13	5.31	2.20	7.88	1.13
	15-30	5.64	10.9	15.0	4.8	2.03	58.1	1.18	9.44	< 1.0	-	0.09	3.56	1.44	5.29	1.26

(1) pH meter and ratio soil: water of 1:2.5; (2) elemental carbon analysis was performed using the CHN elemental analyzer; (3) organic matter (O.M) for modified Walkley and Black method; (4) available P for by Bray II method, (5) S for $CaHPO_4$ extraction; (6) Fe, Cu, Mn and Zn for modified Olsen solution and atomic absorption spectroscopy; (7) exchangeable acidity (A) and exchangeable Al^{+3} for KCl extraction; (8) K^{+1}, Ca^{+2} and Mg^{+2} for atomic emission spectrometer lowing a 1 N KCl extraction; (9) effective cation exchange capacity (CEC); and (10) bulk density (Bd) using cylinder method.

lime was applied three weeks before planting and then two years later with 1.5 kg tree^{-1}. The fertilization totaled 55, 40, 18, 65, and 30 kg ha^{-1} of N, P, K, Mg, and S, respectively, and was divided into six applications until the fifth year of planting. Weed management (herbicide and brush cutter) and leafcutter ants were carried out at least three times a year until the fourth year of plantation and then, the frequency was semiannual. No pruning was done.

Growth and height: diameter ratio. For this first *S. saman* growth phase an equation was adjusted evaluating three linear models and three non-linear models. The models vary in the inclusion or non-inclusion of two predictor variables for estimating the total height: diameter at breast height - 1.3 m (DBH, in cm) and age of plantation (in months). The evaluated models were selected because they are widely used in scientific literature (Picard et al., 2012). The data obtained were of 11 forest inventories until the sixth year of plantation: 17, 21, 25, 28, 32, 35, 41, 49, 54, 60 and 72 months. The DBH was measured with diameter tape and the total height with a clinometer (Pm-5/360 P, Suunto) when it exceeded 10 m. The final survival (72 months) of the planting was evaluated.

Aboveground biomass and nutrients. Based on the forest inventory, in June 2020, or 5.8 years since planting, nine trees were felled which had a DBH range between 12.7 and 25.7 cm (Appendix, Table S1). For each plot, three trees from the central area were selected according to the mean value and ± one standard deviation. In the field, the green biomass was fractioned and weighted in a hanging scale (150 kg of capacity) in seven components: leaves, branches Ø ≤ 1 cm, branches 1 < Ø < 5 cm, branches (wood) Ø ≥ 5 cm, branches (bark) Ø ≥ 5 cm, stem wood and stembark. It was collected samples of 500 g for each component, except for the stem where two discs in the base were cut at 30, 60, and 90% of the commercial height, i.e., with a minimum diameter of 5 cm. After oven drying at 65 °C until constant weight (separating bark wood to establish the bark-wood ratio), the dry biomass of each component and the total biomass per tree (adding the seven components) were estimated. The dry biomass was multiplied by the plant density (400 tree ha^{-1}) to extrapolate to the hectare and obtain the value of each plot by averaging the three trees.

The samples of each component of the three felled trees per plot were mixed to compose a compound sample and to determine the carbon and nutrient concentration. For the components of the stembark and branches Ø ≥ 5 cm, the samples were combined to analyze one sample per plot. The N, S, and C were determined through a CHN elemental analyzer, the P, K, Mg, Ca, Fe, Mn, Zn, and Cu with HNO_3 / H_2O_2 (5:2) and the levels measured by inductively coupled plasma atomic emission spectroscopy (ICP-OES). For the extraction of B, dry digestion and analysis by spectrophotometry were used. The nutrient content of each component per plot was calculated by multiplying the concentration by the biomass of the respective plot and the results were extrapolated to hectare (Mg ha^{-1} or g ha^{-1}). Thus, three repetitions were obtained by the aboveground component.

A sample composed (three subsamples per plot) of collected soil in two depths, 0-15 and 15-30 cm, was sent to the laboratory for its physiochemistry characterization (Table 1). The soil density bulk (meaning three undisturbed samples per plot) at each depth was determined by the weight and volume of an aluminum cylinder (503 cm^3).

Indirect estimation of aboveground biomass. To estimate the aboveground biomass of *S. saman*, an allometric equation based on the statistical model by Schumacher and Hall (1933) was adjusted for the seven tree components and their total biomass. The data used for this model was obtained from nine felled trees. The predictors in the model included diameter at breast height (DBH) and total height (H), both of which were measured following tree felling. The equation used to estimate the biomass was as follows [1]:

$$B = \beta_0 * DBH^{\beta 1} * H^{\beta 2} \quad [1]$$

Where B= aboveground biomass, in kg tree^{-1}; βn= coefficients; DBH= diameter at breast height - 1.3 m, in cm and H= total height, in m.

Fine roots biomass (FRB). At 6.3 years of plantation (December 2020) and finishing the second rainy season (Figure 1), the fine roots biomass was quantified (Ø < 2 mm) in two collecting positions from the base of the stem in relation to the radio of the crown of tree, 50 and 100%, and each one in two soil depths, 0-15 cm and 15-30 cm. In the center of each of the plots, a tree with the DBH closest to the mean and that varied between 16.7 to 22.2 cm was selected, and the value of the FRB of each treatment corresponded to the mean of three collected subsamples (roots + soil) in each tree (repetition) with an aluminum cylinder of 503 cm^3. To collect the subsamples, the projection of the tree canopy area was divided into three parts at equal intervals (120, 240, and 360°), adapting the methodology of Zhang et al., (2021). In the lab, the 36 collected samples (three trees per three subsamples per two depths per two collecting positions) were left in water for 48 hours and the soil was separated from the fine roots by consecutive washings with pressurized water using a sieve (Ø= 2 mm). Dead roots Ø < 2 mm (brittle or fragile and opaque in color) or those that were from other species were visually separated by morphological characteristics with metal tweezers. *Samanea saman* fine root samples were weighed on an analytical balance (Kern – Sohn PCB 1000-1, precision 0.001 g) after oven drying at 65 °C to calculate fine root biomass (FRB, in Mg ha^{-1}).

Above and belowground carbon. The carbon stock in each aboveground component of the tree was estimated by multiplying the carbon concentration by the biomass and extrapolated to one hectare. The organic carbon content of the soil between 0 and 30 cm depth was estimated according to equation [2].

$$SOC = \sum_{i=1}^{k} C_i \times Bd_i \times E_i \; / \; 10 \quad [2]$$

Where SOC= soil organic carbon content between 0-30 cm depth, in Mg ha^{-1}; Ci= carbon concentration of the sampled soil layer, in g kg^{-1}; Bd_i = soil bulk density of the sampled layer, in g cm^{-3}; and E_i = thickness of the sampled soil layer, in cm

The FRB was multiplied by 0.475, which is the fraction of carbon contained in biomass (IPCC 2023). The carbon stock of the forest system in three compartments (aboveground biomass, soil, and fine roots biomass) was assumed at the same age of 5.8 years.

Statistical analysis. The performance of the six allometric height:diameter models were evaluated with the following measures of goodness of fit, and predictive performance: Akaike criterion (AIC), Bayesian Schwarz criterion (BIC), mean absolute error (MAE), square root of the mean square error (RMSE) and adjusted coefficient of determination (R^2). The assumptions of the models were validated visually through the diagnosis of the homoscedasticity of the variances and the normality of the studentized errors. Selection of the best tree-level model prioritized predictive performance criteria over goodness-of-fit measures. The adjusted Schumacher and Hall equation for estimating the seven tree components and total biomass was validated by the adjusted coefficient of determination and the graphical distribution of the residuals. A one-way ANOVA was performed to compare the carbon stock and nutrient contents between the aboveground biomass components, adopting a randomized block design with three repetitions. The blocks were the plots, each of 1,000 m^2. A two-way ANOVA analyzed the FRM values for examining if there was interaction between the soil depths and positions concerning the tree crown radius, adopting a randomized complete block design with three repetitions in a 2 x 2 factorial arrangement (two soil depths x two positions). The blocks were the trees, one selected in each experimental plot of 1,000 m^2. The data were verified with the Shapiro-Wilk normality test and Bartlett's test of homoscedasticity of variances. If the assumptions were not met, there was a log n + 1 transformation for some variables. The means were compared by the Tukey test ($P < 0.05$). All analyses were performed in the SAS 9.4 statistical program.

RESULTS

Growth and height: diameter ratio. After 5.8 years of being planted, the species had an excellent adaptation to the experimental area with a survival rate of 95.5 ± 4.1%, being the DBH and total height (H) of 20.7 ± 5.1 cm and 14.1 ± 2.9 m, respectively (data not shown). Models 2 (ln H = 0.05832 + 0.2416 DBH^2 * age)and 4 (H = 2.204 + 0.4988 DBH – 0.0051 DBH^2), had some non-significant coefficients, while models 1 (ln H 0.605 + 0.6162 ln DBH), 5 (H = 1.397 + 0.2739 DBH + 0.09342) and 6 (H = 2.3026 + 0.6182 DBH) explained the observed data to a lesser extent compared to the others, therefore, these five models were excluded to estimate the height of *S. saman* considering a variation in DBH between 1.5 to 31.7 cm and 1.8 to 21.2 m in H (Table S2). Model 3 (ln H = 1.005 + 0.1664 ln DBH + 0.111 DBH^2), that is, linearized polynomial power, was selected for its better fit and precision of the predictors (lower AIC, BIC, MAE, and RMSE, and higher E %). Analysis of the graphical distribution of the residuals of this model showed that the estimates were free of bias (Appendix, Figure S1).

Aboveground biomass and nutrients. The total aboveground biomass was 51.1 Mg ha^{-1}. The proportion in relation to the total of the tree was significantly higher in the stemwood (41.4%) followed by the branches (wood) Ø ≥ 5 cm, branches 1 ≤ Ø < 5 cm, and leaves (9.6 to 19.4%). The stembark, branches Ø < 1 cm, and branches (bark) Ø ≥ 5 cm (3.5 to 6.1%) presented the lowest proportion of biomass (Table 2).

There were significant differences in the distribution of all the nutrients among the seven components of the aboveground biomass (Table 3 and 4). The total accumulation of macronutrients had the following decreasing order: N > K > Ca > P > Mg > S, varying from 687.2 to 38.7 kg ha^{-1} (Table 3).

Regarding micronutrients, the descending order of accumulation was Fe > B > Mn > Zn > Cu (Table 4). Generally, lower nutrient contents were observed in branches with Ø < 1 cm, branches (bark) with Ø ≥ 5 cm, and stembark, except for Ca, Fe, and Mn, which were notably higher in the stembark. In contrast, leaves, stemwood, and branches with 1 ≤ Ø < 5 cm exhibited higher contents of N, P, K, Mg, S, Zn, Mn, and B (Tables 3 and 4). Branches (wood) with Ø ≥ 5 cm demonstrated intermediate accumulation levels for all micronutrients.

These results are verified when the relative nutrient distribution is analyzed in the aboveground biomass com-

Table 2. Means ± standard error of aboveground biomass and carbon stock (Mg ha^{-1}) by component, fine roots, and soil (0-30 cm), in *Samanea saman* at 5.8 years of plantation. Rionegro, Santander (Colombia).

Medias ± error estándar de la biomasa aérea y stock de carbono (Mg ha^{-1}) por componente, raíces finas y suelo (0-30 cm), en *Samanea saman* a los 5,8 años de plantación. Rionegro, Santander (Colombia).

Component	Biomass	Carbon
leaves	4.92 ± 1.0 (9.6) bc	2.59 ± 0.5 (10.5) bc
branches Ø < 1 cm	2.10 ± 0.3 (4.1) d	1.02 ± 0.2 (4.1) d
branches 1 ≤ Ø < 5 cm	8.09 ± 0.6 (15.8) b	3.84 ± 0.3 (15.6) b
branches (wood) Ø ≥ 5 cm	9.94 ± 2.7 (19.4) b	4.74 ± 1.3 (19.3) b
branches (bark) Ø ≥ 5 cm	1.80 ± 0.5 (3.5) d	0.83 ± 0.2 (3.4) d
stemwood	21.2 ± 2.4 (41.4) a	10.2 ± 1.2 (41.3) a
stembark	3.10 ± 0.3 (6.1) cd	1.43 ± 0.1 (5.8) cd
total aboveground	51.1	24.6
fine roots Ø < 2 mm	8.51	4.04
soil (0-30 cm)		53.0
Total (forest system)		81.7

In parentheses, the proportion of each aboveground component in relation to the total biomass and carbon stock. Means followed by the same letter do not differ significantly (P < 0.05) by the Tukey test.

Table 3. Means ± standard error of macronutrient content (kg ha^{-1}) by component of aboveground biomass of *Samanea saman* at 5.8 years of plantation. Rionegro, Santander (Colombia).

Medias ± error estándar del contenido de macronutrientes (kg ha^{-1}) por componente de biomasa aérea de *Samanea saman* a los 5,8 años de plantación. Rionegro, Santander (Colombia).

Component	N	P ^{a}	K ^{a}	Mg ^{a}	Ca	S ^{a}
leaves	182.0 ± 37.6 a	11.9 ± 2.7 ab	54.4 ± 10.5 a	10.7 ± 2.3 a	35.1 ± 11.6 bc	10.4 ± 2.3 a
branches Ø < 1 cm	36.8 ± 6.1 c	2.9 ± 0.7 bc	14.1 ± 2.8 b	3.0 ± 0.5 bc	18.8 ± 4.4 c	1.9 ± 0.4 c
branches 1 ≤ Ø < 5 cm	116.8 ± 12.7 ab	8.3 ± 0.4 a	54.5 ± 2.1 a	8.2 ± 1.4 a	70.2 ± 9.5 a	6.1 ± 0.0 ab
branches (wood) Ø ≥ 5 cm	71.8 ± 19.6 bc	8.7 ± 2.4 ab	56.7 ± 16.0 a	3.2 ± 0.4 bc	17.6 ± 5.4 c	3.3 ± 0.9 bc
branches (bark) Ø ≥ 5 cm	41.7 ± 11.7 c	1.5 ± 0.4 c	9.2 ± 2.6 b	1.7 ± 0.6 c	35.7 ± 13.7 bc	2.1 ± 0.6 c
stemwood	165.3 ± 6.0 a	14.7 ± 4.2 a	89.2 ± 8.0 a	5.9 ± 1.1 ab	37.0 ± 6.4 bc	6.3 ± 2.7 abc
stembark	72.8 ± 3.9 bc	2.7 ± 0.2 bc	16.1 ± 0.8 b	3.0 ± 0.5 bc	57.4 ± 13.5 ab	3.6 ± 0.3 bc
Total	687.2	50.8	294.2	35.7	271.7	33.7

Means followed by the same letter do not differ significantly (P < 0.05) by the Tukey test. ^{a} data transformed by log n + 1.

ponents. The N, Mg, S, Cu, and Mn were higher in the leaves (26.5 a 34.8%) followed by the stemwood (16.4 a 24.3%). In the branches (bark) Ø ≥ 5 cm (4.9 to 9.3%) and branches Ø < 1 cm (3.8 to 9.7%) were lower. The P, K, Fe, Zn, and B were higher in the stemwood (26.0 to 37.8%) and lower in the branches (bark) Ø ≥ 5 cm (3.0 to 8.8%) or branches Ø < 1 cm (3.1 to 8.4%). The Ca accumulated more in the branches 1 ≤ Ø < 5 cm (25.7%) followed by the stembark (21.1%), as opposed to the branches (bark) Ø ≥ 5 cm which was lower (6.5%) (Appendix, Figure S2).

Based on the evaluated data, for predicting aboveground biomass in trees ranging from 9.1 – 14.5 m in height and 12.7 – 25.7 cm in DBH, residual diagnostics showed a homogeneous, randomly dispersed pattern, confirming that the assumptions of normality and homoscedasticity were satisfied. No systematic trend was detected in the residuals for branches Ø ≤ 1 cm, branches (wood + bark) Ø ≥ 5 cm and a total of tree (Appendix, Fig. S3). The equation generated for these components best explained the variation of the observed data (R^2 = 0.85 to 0.97), while in the leaves (R^2 = 0.58) and stembark (R^2 = 0.64) it was the opposite (Table 5).

Carbon and fine roots. The aboveground carbon stock added up to 24.6 Mg ha^{-1} and followed a pattern of accumulation identical to the aboveground biomass being significantly higher in the stemwood with 10.2 Mg ha^{-1} and lower in the stembark, branches Ø < 1 cm and bran-

Table 4. Means ± standard error of micronutrient content (g ha^{-1}) by component of aboveground biomass of *Samanea saman* at 5.8 years of plantation. Rionegro, Santander (Colombia).

Medias ± error estándar del contenido de micronutrientes (g ha^{-1}) por componente de biomasa aérea de *Samanea saman* a los 5,8 años de plantación. Rionegro, Santander (Colombia).

Component	Fe ^{a}	Cu ^{a}	Mn ^{a}	Zn ^{a}	B
leaves	495.6 ± 32.9 ab	67.6 ± 21.5 a	170.6 ± 34.6 a	40.1 ± 7.1 ab	144.6 ± 29.1 ab
branches Ø < 1 cm	100.9 ± 18.5 c	18.9 ± 2.8 c	21.6 ± 2.2 c	26.0 ± 1.5 bc	44.1 ± 6.8 c
branches 1 ≤ Ø < 5 cm	465.7 ± 86.0 bc	32.1 ± 6.5 bc	80.4 ± 12.5 ab	72.5 ± 14.6 a	162.1 ± 16.1 ab
branches (wood) Ø ≥ 5 cm	179.9 ± 67.9 bc	18.2 ± 4.5 c	49.7 ± 13.3 bc	39.5 ± 8.9 ab	98.1 ± 22.0 b
branches (bark) Ø ≥ 5 cm	292.4 ± 147.4 bc	3.6 ± 0.8 d	52.8 ± 17.1 bc	14.3 ± 3.4 c	46.2 ± 14.3 bc
stemwood	1,248.0 ± 441.8 a	47.1 ± 4.8 ab	106.0 ± 12.2 ab	90.8 ± 12.9 a	201.5 ± 20.1 a
stembark	521.4 ± 183.7 bc	6.6 ± 0.2 d	88.9 ± 11.2 ab	25.9 ± 0.6 bc	79.2 ± 7.9 bc
Total	3,303.8	194.1	569.9	309.0	775.8

Means followed by the same letter do not differ significantly (P < 0.05) by the Tukey test. ^{a} data transformed by log n + 1.

Table 5. Adjusted equation of the Schumacher and Hall (1933) model to estimate biomass by component and total aboveground of *Samanea saman* with 5.8 years of plantation. Rionegro, Santander (Colombia).

Ecuación ajustada del modelo Schumacher y Hall (1933) para estimar el contenido de biomasa (B) por componente y total aéreo de *Samanea saman* con 5,8 años de plantación. Rionegro, Santander (Colombia).

Component	Equation	R^2	Mean (kg tree^{-1})	
			E	O
leaves	$0.03677 * DBH^{2.25588} * H^{-0.34574}$	0.58	12.5	12.3
branches Ø ≤ 1 cm	$0.0003525 * DBH^{2.0660379} * H^{1.34556}$	0.85	5.17	5.26
branches 1 < Ø < 5 cm	$3.501 * DBH^{2.68} * H^{-2.446}$	0.72	20.4	20.2
branches (wood) Ø ≥ 5 cm	$0.0000000302 * DBH^{4.373} * H^{1.941}$	0.97	24.8	24.8
branches (bark) Ø ≥ 5 cm	$0.00000919 * DBH^{4.57} * H^{-2.713}$	0.94	4.53	4.50
stemwood	$0.2768 * DBH^{1.9041} * H^{-0.1572}$	0.74	52.7	53.0
stembark	$0.7753 * DBH^{1.4915} * H^{-0.8317}$	0.64	7.71	7.74
total	$0.1323 * DBH^{2.5399} * H^{-0.2748}$	0.89	127.3	127.8

R^2 = adjusted coefficient of determination, estimated mean (E) derived from the allometric equation and observed mean (O) derived from the felled trees. DBH = diameter at breast height at 1.3 m, in cm; H = commercial height, in m.

ches (bark) Ø ≥ 5 cm, between 3.4 to 5.8 Mg ha^{-1} (Table 2). There was a variation of the FRB (minimum of 6.62 Mg ha^{-1} and maximum of 9.51 Mg ha^{-1}) with the increase of the depth of the soil from 0-15 cm to 15-30 cm, however, no significant differences were found between the factors evaluated or their interaction, with the average being 8.51 Mg ha^{-1} (Figure S4). The total carbon stock of the forest system (aboveground biomass + fine roots + soil) up to 30 cm depth was 81.7 Mg ha^{-1}, 65% being in the soil and 5% in the fine roots (Table 2).

DISCUSSION

The aboveground biomass stock of *S. saman* at the age assessed (51.1 Mg ha^{-1}) was within the range recorded for other species introduced in the tropics. For example, 10-year-old *Pinus caribaea* plantations in Brazil reached 75.0 Mg ha^{-1}, while six-year-old Eucalyptus clones in China ranged from 29.3 to 77.1 Mg ha^{-1} (Gomes et al., 2019; Zhang et al., 2022). A 4.8-year-old Brazilian fern tree (*Schizolobium parahyba* (Vell.) Blake)) plantation produced between 20.0 and 40.6 Mg ha^{-1} (Delarmelina et al., 2023). To facilitate even more accurate comparisons with native and non-native species, further trials with different planting densities are recommended, as planting density directly affects stem diameter, volume, and ultimately overall productivity (Santos et al., 2017; Delarmelina et al., 2023). When converting biomass to carbon stock, the IPCC default factor of 0.475 is typically applied (IPCC, 2023). However, our specific analyses of the tree's components revealed a notable variability in carbon concentration: the leaves contained 52.7%, while the stembark contained 46.3% (Appendix, Table S3). Thus, by incorporating these directly determined carbon concentrations rather than a single generic coefficient, indirect carbon estimates for the aboveground biomass of *S. saman* may be more accurate.

No significant dry periods were recorded in this study, except in 2015, which had two consecutive months with less than 60 mm of precipitation (Figure 2). High historical rainfall and mountainous terrain explain the low soil fertility prior to planting (3.42 cmolc kg^{-1} of exchangeable bases) due to nutrient leaching, especially of Ca^{2+}, Mg^{2+}, and K^{+} (Arias et al., 2011; Zhang et al., 2022). Despite these conditions, *S. saman* showed remarkable productivity at the study site, probably also due to its drought tolerance, a characteristic that favors its widespread use in the Caribbean grasslands of Colombia (Lombo et al., 2023). The high potential of *S. saman* for reforestation, particularly its survival and growth under adverse conditions, has been demonstrated in abandoned alluvial gold mining areas in the Nechí River basin, Antioquia (2,000 – 4,000 mm year^{-1}), Colombia, after 10 years (Lozano-Báez et al., 2022).

Approximately 50% of the nutrient content of *S. saman* was concentrated in the leaves and branches Ø < 5 cm, which constituted 30% of the aboveground biomass. In general, the leaves had the highest nutrient concentration and accumulated up to three times more Mg, S, Cu, and Mn than their respective proportion of aboveground biomass. A similar situation was observed with the stembark in the case of Ca, Fe, and Mn, which accumulated on average 18% of the total of these nutrients (Appendix, Tables S3 and S4). Leaves and stembark are a valuable source of nutrients for the soil, especially Ca and micronutrients (Dick et al., 2017; Gomes et al., 2019). Forest residue management is essential for maintaining soil fertility over time (Van Bich et al., 2018). Given the soil and climate conditions of the study site, retaining leaves and thin branches < 5 cm in the *S. saman* field could reduce the need for fertilization. In addition, natural pruning of the saman tree provides a constant supply of nutrients to the soil and could improve its natural reserves. In fact, the accumulation of some nutrients from *S. saman* in the aboveground biomass was higher than that observed in plantations of gmelina (*Gmelina arbórea* Roxo) (6 or 11 years old; total N = 128 – 352 kg ha^{-1}, P = 43 kg ha^{-1}, K = 93 – 208 kg ha^{-1}, Ca = 39 – 105 kg ha^{-1}), *Eucalyptus* sp. (5 or 10 years old; total N = 156 – 268 kg ha^{-1}, P = 7 - 33 kg ha^{-1}; Ca = 81 – 130 kg ha^{-1}), *Pinus* sp. (10 years old; total N = 142 – 149 kg ha^{-1}; Mg = 21 kg ha^{-1}), and other species (6 years old; total N = 111 – 333 kg ha^{-1}, P = 2 - 13 kg ha^{-1}) evaluated in tropical regions (Chijioke 1980; Onyekwelu et al., 2006; Arias et al., 2011; Santos et al., 2017; Gomes et al., 2019; Zhang et al., 2022).

The equations generated for the estimation of the aboveground biomass of *S. saman*, as expected, did not present a good adjustment for the leaves (high variation of the data) (Table 5). In plantations with native species in Brazil and Costa Rica, the leaves were the component of the tree with the worst fit and are explained by the influence exerted by other variables such as canopy architecture, phenology, or seasonality of rainfall (Fonseca et al., 2023; Delarmelina et al., 2023). The allometric equation that was adjusted for the height estimation as a function of DBH and age facilitates the indirect estimation of the aboveground biomass and carbon stock, which avoids tree falling, which is a more costly method. *S. saman* is a tree whose broad, branched crown made direct height measurements difficult in this study, which could be generalized to the rugged terrain typical of the lowlands of the three branches of the Colombian Andes. Other plantation sites and broader ranges of height and DBH should be considered to improve calibration. Additionally, the inclusion of basic wood density as a predictor variable is recommended given the great diversity of forests in Colombia (Duque et al., 2017).

The treatment of 0–15 cm (soil depth) x 50% (position of fine root collection in relation to the crown radius) was the only one that presented a high coefficient of variation (30%) for FRB. This supports the accuracy of the data (Figure 3). Three factors probably explain the lower FRB value in the deepest soil layer (15-30 cm) and in the sampling site furthest to the tree trunk (100%

of the crown radius): 1) the high density of plantation adopted from the experiment for this species, 2) the soil depth evaluated up to 30 cm which could have been insufficient to reach the exploration limit of fine roots, and 3) the collection during the end of the rainy period which is when, theoretically, more intense production of fine roots occurs. Tree crown projection calculated from eight directional crown radii averaged 70.0 m^2 $tree^{-1}$ (data not shown), indicating that the canopy of planting was very dense after six years of planting. In the native vegetation of the southern Amazonian mesoregion with a tropical rainy climate (monsoon-type rain), the production of FRB was higher during the rainy period being very similar to the values shown in the present study (8.19 Mg ha^{-1} versus 8.51 Mg ha^{-1}). But it was lower in the 20-year reforestation plots with teca (*Tectona grandis* L.) and native species (3.57 Mg ha^{-1}) (Bello et al., 2021). Although the fine roots of *S. saman* represented 5% of the forest system's carbon stock, they are responsible for the absorption of water and nutrients (Zhang et al., 2021) and again demonstrate the high capacity to grow on poor-quality soils.

The soil layer of the plantation, with a depth of up to 30 cm, had a higher carbon content (53.3 Mg ha^{-1}), for example, than that observed in the Amazon for secondary forests or grasslands with *Brachiara* sp, 42.6 and 49.6 Mg $ha^{-1,}$ respectively (Olaya-Montes et al., 2021). For a subtropical secondary forest in Minas Gerais (Brazil), the carbon content value for a depth of up to 20 cm was 55 Mg ha^{-1} (Dantas et al., 2021) and, for an agroforestry system with coffee in the Peruvian Andes, the concentration varied between 82 and 101 Mg ha^{-1} for depths of up to 30 cm, depending on the forest species and the age of the plantation (Ehrenbergerová et al., 2016). However, it should be noted that it is important to compare the results of *S. saman* reforestation with a native forest ecosystem reference near the study area. *S. saman* is a semi-deciduous species that follows an annual defoliation pattern, as verified in the same study area (Pabón et al., 2023). The successive contributions of leaf litter and branches to the soil may have contributed to the soil carbon reserves reaching the values observed.

CONCLUSIONS

The aboveground biomass production of *S. saman* was 51.1 Mg ha^{-1}, highlighting the species' significant carbon sequestration potential. Leaves and branches with Ø < 5 cm accounted for 30% of the aboveground biomass but accumulated approximately 50% of the nutrients, underscoring their critical role in replenishing soil nutrients. Additionally, the soil and fine roots (Ø < 2 mm) at depths of up to 30 cm stored 70% of the carbon stock within the forest system. In the lowlands of the Colombian Andes, *S. saman* shows great promise as a native species for rehabilitating agriculturally degraded mountain landscapes under low fertility conditions. This study contributes to enhancing the accuracy of biomass and carbon stock estimations, both direct and indirect, while supporting the sustainable management of *S. saman* plantations.

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AUTHORS CONTRIBUTION

AIP, JJZ: conceptualization of the work, formal analysis, supervision, interpretation of results, and writing, and review. PMV, SVM and MVWC: interpretation of results, writing and review.

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APPENDIX

Table S1. Dendrometric measurements of the felled *Samanea saman* trees from the study with 5.8 years of plantation. Rionegro, Santander (Colombia).

Medidas dendrometricas de los árboles derribados de *Samanea saman* del estudio con 5,8 años de plantación. Rionegro, Santander (Colombia).

Block	Tree	dbh (cm)	h (m)	hc (m)	cd (m)
1	T1	12.7	9.1	6.7	7.4
	T2	15.0	9.9	6.5	7.4
	T3	19.9	12.9	9.4	9.9
2	T4	16.3	13.5	9.1	5.1
	T5	21.7	14.4	10.8	10.9
	T6	24.0	14.5	11.7	14.3
3	T7	15.6	13.1	10.0	6.6
	T8	20.8	13.0	9.5	9.5
	T9	25.7	12.6	10.5	12.3

dbh = diameter at breast heigh at 1.3 m; ht = height at top of tree; hc = commercial height (Ø < 5 cm); cd = crown diameter.

Table S2. Estimated coefficients (P value) and selection criteria of the adjusted diameter-height allometric models of *Samanea saman* at 5.8 years of plantation. Rionegro, Santander (Colombia).

Coeficientes estimados (Valor *P*) y criterios de selección de los modelos alométricos diámetro-altura ajustados de *Samanea saman* a los 5,8 años de plantación. Rionegro, Santander (Colombia).

Model	Coefficients			AIC	BIC	MAE	RMSE	E %
	β_0	β_1	β_2					
[1] $lnH = \beta_0 + \beta_1 ln(DBH) + \varepsilon_i$	0.6050 (***)	0.6162 (***)	-	-357	-327	0.173	0.223	76.0
[2] $lnH = \beta_0 + \beta_1 ln(DBH^2 * age) + \varepsilon_i$	0.05832 (ns)	0.2416 (***)	-	-503	-451	0.167	0.215	77.7
[3] $lnH = \beta_0 + \beta_1 \in DBH + \beta_2 lnDBH^2 + \varepsilon_i$	1.0050 (***)	0.1664 (*)	0.111 (***)	-389	-357	0.165	0.214	77.9
[4] $H = \beta_0 + \beta_1 DBH + \beta_2 DBH^2 + \varepsilon_i$	2.2040 (***)	0.4988 (***)	-0.00051 (ns)	3,199	3,233	1.424	1.971	73.3
[5] $H = \beta_0 + \beta_1 DBH + \beta_2 a \geq + \varepsilon_i$	1.3970 (***)	0.2739 (***)	0.0934 (***)	3,083	3,120	1.463	1.953	73.8
[6] $H = \beta_0 + \beta_1 DBH + \varepsilon_i$	2.3026 (***)	0.6162 (***)	-	3,168	3,208	1.439	2.001	72.4

Models: [1] linearized power, [2] double input linearized power, [3] linearized polynomial power ,[4] polynomial ,[5] linear multiple and [6] linear. AIC = Akaike's criterion; BIC = Schwarz Bayesian criterion; MAE= mean absolute error; RMSE = square root of mean square error and E= efficiency. DBH= diameter at breast heigh - 1.3 m (in cm); H= height (in m); age (in months) and εi= random error. *** statistically significant at 5%. ns= not significative.

Table S3. Carbon and macronutrient concentration (%) by component of the aboveground biomass of *Samanea saman* at 5.8 years of plantation. Rionegro, Santander (Colombia).

Concentración de carbono y macronutrientes (%) por componente de la biomasa aérea de *Samanea saman* a los 5,8 años de plantación. Rionegro, Santander (Colombia).

Component	C	N	P [a]	K	Mg [a]	Ca	S
leaves	52.7 ± 0.43 a	3.70 ± 0.15 a	0.24 ± 0.02 a	1.11 ± 0.02 a	0.22 ± 0.00 a	0.69 ± 0.21 b	0.21 ± 0.01 a
branches Ø < 1 cm	48.4 ± 0.24 bc	1.75 ± 0.04 c	0.14 ± 0.01 b	0.67 ± 0.06 b	0.15 ± 0.02 b	0.87 ± 0.08 b	0.09 ± 0.01 bc
branches 1 ≤ Ø < 5 cm	47.5 ± 0.13 bc	1.44 ± 0.06 c	0.10 ± 0.00 bc	0.68 ± 0.07 b	0.10 ± 0.01 c	0.89 ± 0.17 b	0.08 ± 0.01 c
branches (wood) Ø ≥ 5 cm	47.5 ± 0.40 bc	0.80 ± 0.16 d	0.09 ± 0.01 c	0.58 ± 0.07 bc	0.04 ± 0.02 d	0.19 ± 0.05 d	0.04 ± 0.01 d
stemwood	47.9± 0.39 bc	0.80 ± 0.07 d	0.07 ± 0.02 c	0.43 ± 0.03 cd	0.03 ± 0.01 d	0.18 ± 0.04 d	0.03 ± 0.01 b
bark	46.3 ± 0.48 c	2.36 ± 0.08 b	0.09 ± 0.00 c	0.52 ± 0.03 d	0.10 ± 0.01 c	1.82 ± 0.37 a	0.12 ± 0.01 d

Means followed by the same letter do not differ significantly (P < 0.05) by the Tukey test. [a] data transformed by log n + 1.

Table S4. Concentration of micronutrients (mg g^{-1}) per component of the aboveground biomass of *Samanea saman* at 5.8 years of plantation. Rionegro, Santander (Colombia).

Concentración de micronutrientes (mg g^{-1}) por componente de la biomasa aérea de *Samanea saman* a los 5,8 años de plantación. Rionegro, Santander (Colombia).

Component	Fe [a]	Cu [a]	Mn [a]	Zn [a]	B
leaves	107.5 ± 17.5 b	13.3 ± 1.8 a	34.8 ± 2.2 a	8.24 ± 0.4 bcd	29.5 ± 2.1 ab
branches Ø < 1 cm	49.3 ± 8.0 ab	9.34 ± 1.5 a	10.55 ± 1.0 b	12.9 ± 1.6 a	21.1 ± 0.5 c
branches 1 ≤ Ø < 5 cm	56.7 ± 7.1 ab	3.88 ± 0.6 b	9.81 ± 0.9 b	8.78 ± 1.2 b	20.0 ± 0.5 ab
branches (wood) Ø ≥ 5 cm	18.1 ± 3.6 b	1.90 ± 0.2 c	5.00 ± 0.0 c	4.41 ± 1.0 cd	10.3 ± 0.8 bc
stemwood	66.3 ± 32.1 ab	2.23 ± 0.0 bc	5.00 ± 0.0 c	4.58 ± 1.3 c	9.57 ± 0.5 a
bark	174.9 ± 62.3 a	2.17 ± 0.2 bc	28.6 ± 2.3 a	8.52 ± 0.9 bc	25.5 ± 0.4 c

Means followed by the same letter do not differ significantly ($P < 0.05$) by the Tukey test. [a] data transformed by log n + 1.

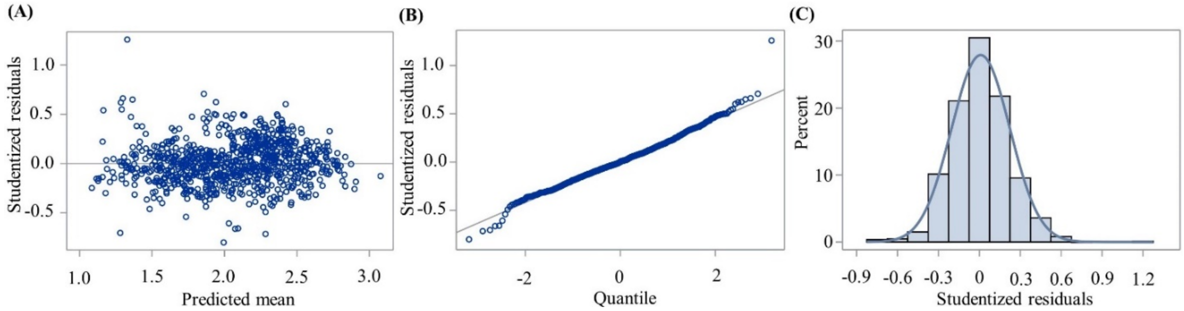

Figure S1. Plots of studentized residuals versus predicted values (A), versus quantile-quantile (B) and versus 95% confidence bands (C) of the selected allometric model.

Gráficos de residuales estudentizados versus valores predichos (A), versus cuantil (B) y versus bandas de confianza al 95 % (C) del modelo alométrico seleccionado.

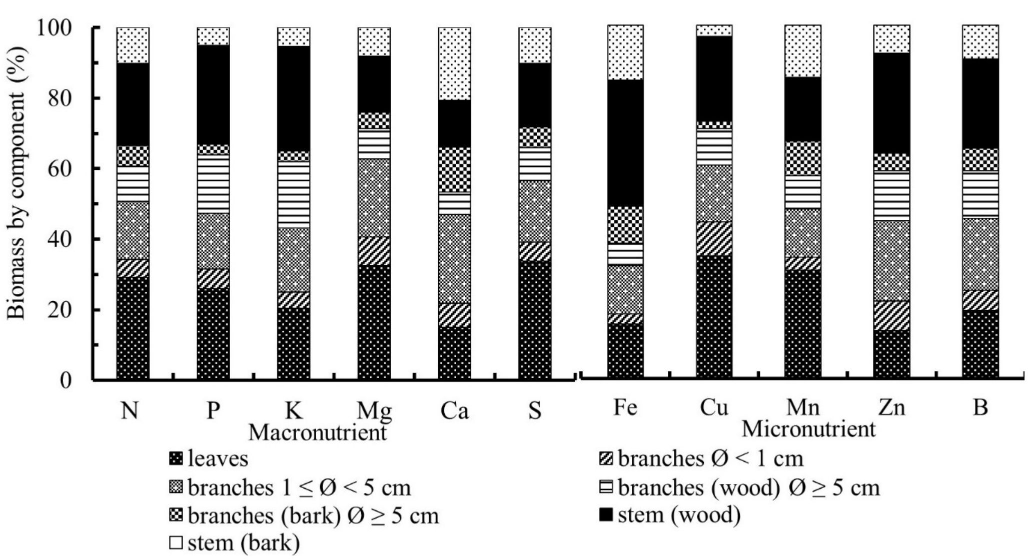

Figure S2. Distribution of nutrients by component of the aboveground biomass of *Samanea saman* at 5.8 years of plantation. Rionegro, Santander (Colombia).

Distribución de nutrientes por componente de la biomasa aérea de *Samanea saman* a los 5,8 años de plantación. Rionegro, Santander (Colombia).

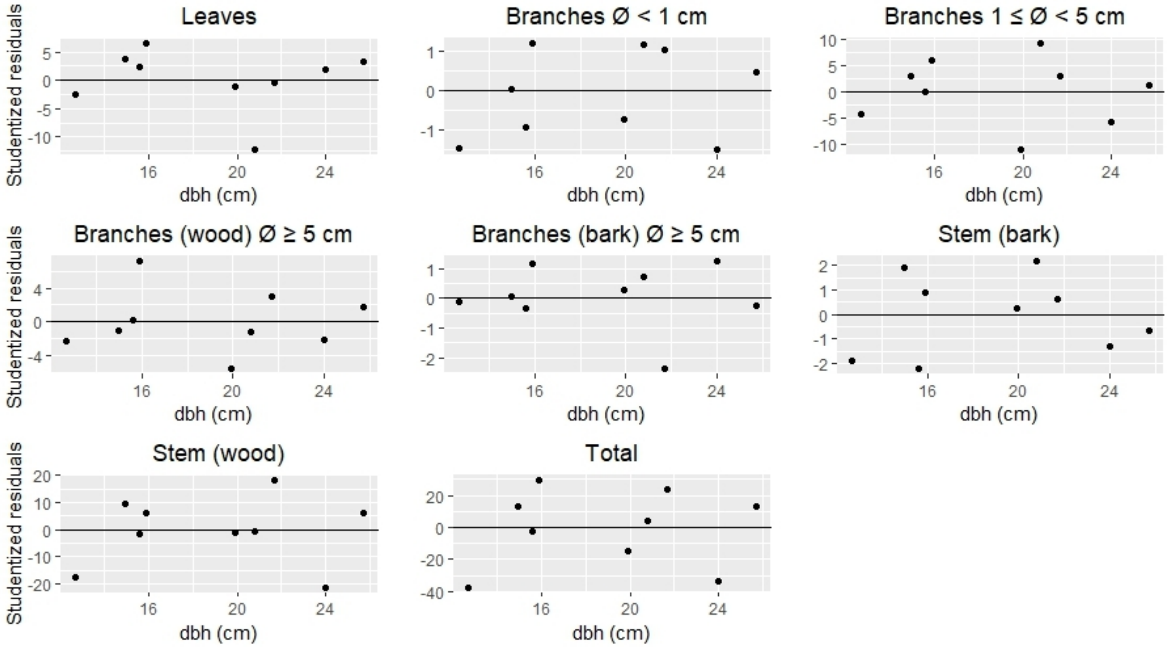

Figure S3. Residue distribution based on DBH for the biomass of the seven components and total aboveground of *Samanea saman* at 5.8 years of plantation. Rionegro, Santander, Colombia.

Distribución de residuos en función del dap para o contenido de biomasa de los siete componentes y total aéreo de *Samanea saman* a los 5,8 años de plantación. Rionegro, Santander, Colombia.

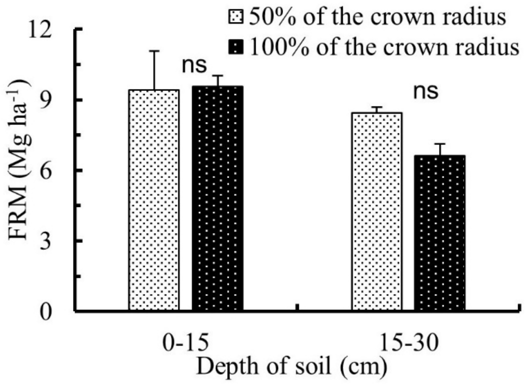

Figure S4. Fine roots biomass (Mg ha^{-1}) in two soil depths (0-15 cm and 15 - 30 cm) and two positions from the stem in relation to the crown radius of the tree (50 and 100%), in *Samanea saman* at 6.3 years of plantation. Rionegro, Santander (Colombia). The lines above the bars indicate the standard error (n = 3). ns = not significant statistically at 5%.

Biomasa de raíces finas (Mg ha^{-1}) en dos profundidades de suelo (0-15 cm y 15 - 30 cm) y dos posiciones desde el fuste con relación al radio de copa del árbol (50 y 100%), en *Samanea saman* a los 5.8 años de plantación. Rionegro, Santander (Colombia). Las líneas sobre las barras indican el error estándar (n = 3). ns = no significativo estadísticamente 5%.