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INVESTIGACIÓN

Simulation of the growth and yield of the species Gmelina arborea Roxb

Simulación del crecimiento y el rendimiento de la especie Gmelina arborea Roxb

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Abstract

Forests are being threatened worldwide mainly due to the increased demand for wood, 50 % of which is extracted from forests. This is largely because the forest plantations which supply the market grow at a slow rate. Given that, one of the fundamental goals of forestry research is the construction of growth and yield models to be used as a planning tool. In this way, the proposal of this work is to show how, through the modeling and simulation of the growth of a forest stand, the uncertainty of investors is reduced because it allows for the quantification of the production of wood that will be obtained. The study was based on data obtained from inventories conducted between 2012 and 2015 in 31 permanent plots of Gmelina arborea Roxb., located in three municipalities of Tolima: Armero, Coello, and Guamo. Based on the inventory data, three regression models were implemented. These results will be particularly useful for silvicultural management planning as the implemented methodology can be applied in other regions of the world and with other varieties of forest species. As an additional stimulus for investors, the simulation is also able to quantify carbon capture in a technical way to be offered in the carbon bond market.
Keywords: Growth Simulation for forestry, Silvicultural Management, Forest Stand, Carbon Capture,

Resumen

Los bosques a nivel mundial se están viendo amenazados principalmente por el aumento de la demanda de madera, ya que más del 50 % de esta se extrae directamente de ellos. Esto se debe en gran medida a que las plantaciones forestales

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crecen a un ritmo lento y abastecen el mercado. Por ello, uno de los objetivos fundamentales de la investigación forestal es la construcción de modelos de crecimiento y rendimiento que sirvan como herramienta de planificación. La propuesta de este trabajo es mostrar cómo a través de la modelación y simulación del crecimiento de un rodal forestal se reduce la incertidumbre de los inversionistas porque permite cuantificar la producción de madera que se obtendrá. El estudio se basó en datos obtenidos de inventarios realizados entre 2012 y 2015 en 31 parcelas permanentes de Gmelina arborea Roxb., ubicadas en tres municipios del Tolima: Armero, Coello y Guamo. Con base en los datos del inventario, se implementaron tres modelos de regresión. Estos resultados serán particularmente útiles para la planificación del manejo silvícola, ya que la metodología implementada puede ser aplicada en otras regiones del mundo y con otras variedades de especies forestales. Como estímulo adicional para los inversionistas, en la simulación es posible cuantificar la captura de carbono de manera técnica para ser ofrecido en el mercado de bonos de carbono.

Palabras clave: Simulación de crecimiento para silvicultura, gestión silvícola, masa forestal, captura de carbono,

INTRODUCTION

The importance of forest conservation in the world lies in the fact that, together with the oceans, forests are the main sinks of greenhouse gases, especially carbon dioxide. According to FAO information (FAO, 2020b), by 2020 forests occupied 31 % of the earth's surface with about 4,060 million hectares (ha). Of these forests, 1,827 million hectares (ha) correspond to the tropical domain (45 %).
These forests are heavily threatened by deforestation. According to the same report, by 2020, around 4.5 million hectares of forest will be lost worldwide each year, especially in South America and Africa, where the world's largest tropical forests are located: the Amazon and the Congo rainforest. Africa has the highest annual rate of deforestation: for the period 2010-2020, about 3.9 million hectares (ha) of forest were lost per year. For the same period, South America had an estimated annual loss of 2.6 million hectares (ha) of forest. On the contrary, for the period in question, the loss of natural forest by deforestation is being compensated by reforestation in Asia (1.2 million hectares (ha) per year) and Europe (0.3 million hectares per year) (FAO, 2020b).
From 1990 to 2020, an estimated 420 million hectares of forests have been lost worldwide (FAO, 2020b). The main causes of deforestation are the increase in the agricultural frontier and the production of wood products used in industry worldwide, estimated at two thirds of total production (Thiffault *et al.*, 2021).
According to the Living Forests Model, the total volume of wood extracted from the world's forests estimated for 2016 was 3700 million m3. It is expected that by 2030, the global demand for wood will

be approximately double (Dash, Moore, Lee, Klápště, & Dungey, 2019).

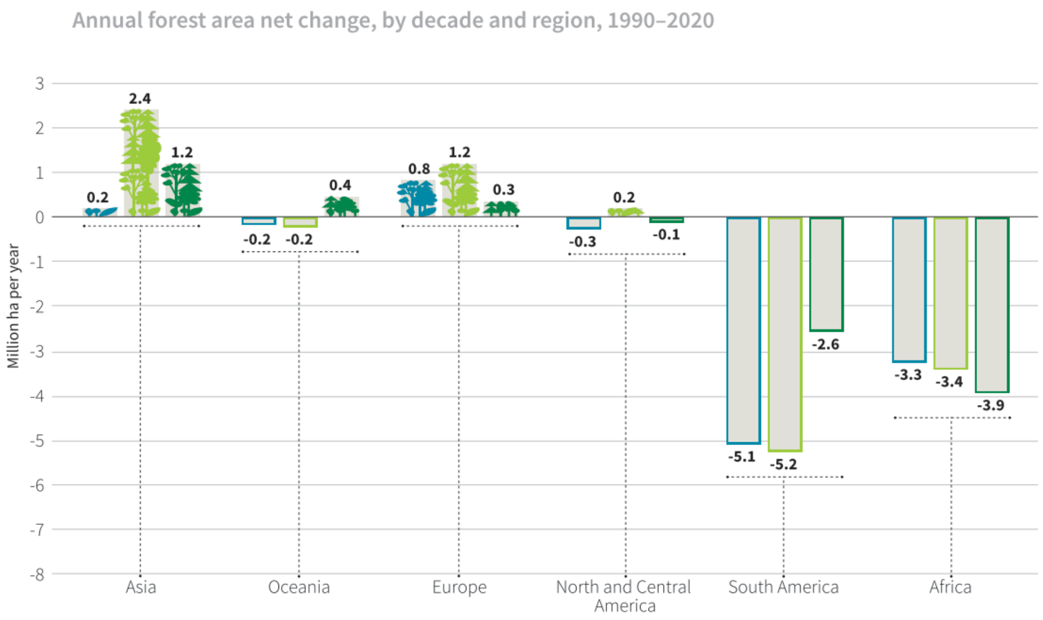

Figure 1. Annual forest area net change, by decade and region, 1990–2020

Source: (FAO, 2020a)

This loss of natural forest directly impacts carbon sequestration: global forest carbon stocks decreased between 1990 and 2020 from 668 Gt to 662 Gt (FAO, 2020b).

Given these prospects and the need for wood as a raw material for various industries such as furniture, construction, paper and fuel, the task of the forestry sector is to ensure that the extraction of timber products produced by natural forests is conducted under management and conservation schemes. Likewise, because the regeneration of natural forests is relatively slow with growth rates of approximately 2 m3/ha/year, it is necessary to increase forest plantations which, under improvement programs, optimize the planting of desired species and the application of silvicultural treatments, enabling them to supply a greater percentage of the timber needed by industry. In addition, they provide other ecosystem services such as wildlife habitats, conservation, and carbon sequestration, vital for mitigatinganthropogenic climate change (Dash *et al.*, 2019; Thiffault *et al.*, 2021).

Colombia is a country with a biodiversity that places it among the 17 most megadiverse countries on the planet: Ït is the first most biodiverse country per square kilometer in the world, the second most biodiverse in natural resources, and the sixth with the greatest water wealth on the planet". Colombia ranks first in birds and orchids; second in the greatest variety of plants, amphibians, butterflies, and freshwater fish; third in the world with the most palms and reptiles; fourth in mammals: and fifth in marine and continental ecosystems"(DANE, 2021).

Table 1. Total forest carbon stock, by region and subregion, 1990–2020

Region/subregion	**1990**	**2000**	**2010**	**2020**
Eastern and Southern Africa	30 932	29 642	27 978	26 250
Northern Africa	2 338	2 242	2 190	2 090
Western and Central Africa	61 005	58 253	55 745	52 546
Total Africa	94 274	90 137	85 913	80 886
East Asia	27 110	30 261	33 908	37 907
South and Southeast Asia	45 804	43 792	43 071	41 468
Western and Central Asia	4 180	4 511	4 959	5 358
Total Asia	77 093	78 564	81 938	84 733
Europe excl. Russian Federation	31 625	34 260	36 833	39 192
Total Europe	158 744	162 457	168 069	172 442
Caribbean	1 552	1 783	1 977	2 098
Central America	4 988	4 617	4 270	4 069
North America	136 644	137 730	139 324	139 951
Total North and Central America	143 184	144 131	145 572	146 118
Total Oceania	33 338	33 111	33 077	33 063
Total South America	161 765	154 917	147 917	144 846
WORLD	**668 399**	**663 316**	**662 485**	**662 088**

Source: (FAO, 2020b)

However, due to the high rate of deforestation, the situation in Colombia is of great concern with respect to other countries in the region. The recent Global Forest Resources Assessment (FRA)

Colombia report indicates that an average of 199,285 hectares of natural forest have been lost per year. See Table 1 (FAO, 2020b).

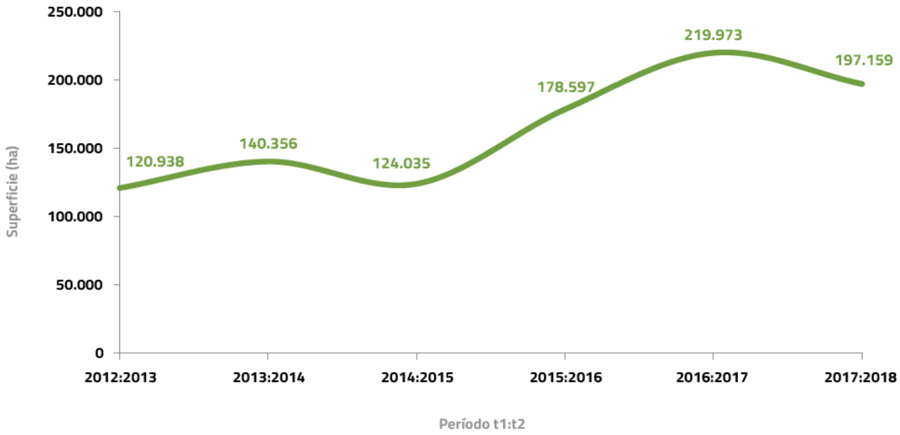

Figure 2. Deforested area (hectares) 2012 - 2018

Source: (DANE, 2021)

Contrary to what the country needs, the area of plantations established annually has decreased. While in 2012 there was an increase of 35,388 new hectares of planted forests, by 2018 forest plantations barely increased by 10,075 hectares (ha). See Figure 2.

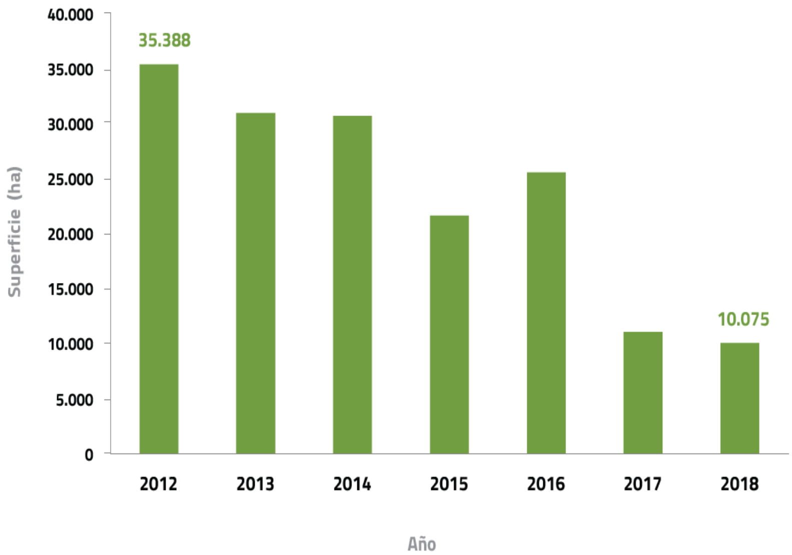

Figure 3. Area of commercial plantations established annually (a). 2012-2018

Source: (DANE, 2021)

In the PND 2018 - 2022 "Pact for Colombia, Pact for Equity", the need to achieve a balance between conservation and production is proposed. Under the slogan Çonserve by producing and produce by conserving", it seeks to implement actions to make the forestry sector more productive and to mitigate the environmental impact caused by the exploitation of natural forests through the strengthening of research, public management, and dialogue and environmental education of the communities.

Because forestry plantations are long-term crops, farmers, owners of land suitable for forestry, and investors who expect short-term profitability are discouraged from investing in the sector.

To make the forestry sector more attractive, it is necessary to increase technical knowledge, especially of those species that, due to their rapid growth and yield, can attract investment. This includes planning with the help of yield and growth models and, as an added value, the periodic quantification of carbon sequestration within the simulation, as a technical basis for the issuance and marketing of carbon credits or bonds which would provide additional periodic profitability.

In the Forestry Statistical Bulletin which dictates the policies of the Directorate of Agricultural and Forestry Chains of the Ministry of Agriculture, we highlight the commercial forestry species as of June 2019, laying out the number of hectares per area and per species (Ministerio de Agricultura y Desarrollo Rural, 2019).

Among the promising species in Colombia, the University of Tolima has been working on the technological package of the forest species Gmelina arborea Roxb. This tropical species was introduced into Colombia more than 20 years ago and is currently considered one of the most promising in forest production, not only for its rapid growth, but also for the quality of its wood and excellent adaptation. In different Colombian Regions, it has been possible to reduce harvesting periods for this species to less than 10 years in Bolívar and Magdalena on the Atlantic coast, in Casanare, Vichada and Meta, in the Orinoquía, in Urabá Antioqueño, in the middle Magdalena and in the inter-Andean valleys of the Cauca and Magdalena rivers (departments of Valle, Tolima and Huila).

The purpose of this study is to model and simulate the growth and yield of the promising species Gmelina arborea Roxb, including the calculation of biomass and CO_2 equivalent for a one hectare stand.

For the simulation, data from the four measurements of permanent plots of the forest species Gmelina arborea Roxb. located in the department of Tolima, was used. Based on the information available, and as a strategy for planning, we consider it necessary to model and simulate the growth and yield of this species, which allows for the projection and quantification of production, and also to determine the conditions necessary to achieve the desired objectives.

Table 2. Species of Commercial Forest Plantations as of June 2019

Species of Commercial Forest Plantations as of June 2019					
Species	**High suitability zones UPRA**				
	Caribe	**Eje Cafetero**	**Orinoquía**	**Others**	**Total**
Other Pines	83	62.127	45.669	4.691	112.570
Pinus patula	12	62.531	1.000	11.860	75.403
Native species	24.851	24.357	2.827	21.740	73.775
Other Eucalyptus	13.965	8.136	35.128	11.851	69.081
Acacia mangium	15.387	8.236	40.357	1.672	65.652
Eucalyptus grandis	1	42.054	75	7.661	49.791
Tectona grandis	20.187	22.518	1.849	3.935	48.490
Introduced species	238	17.331	20.327	4.155	42.051
Gmelina arborea	24.605	4.256	197	958	30.017
N.c.p	295	862	213	1.939	1.939
Grand Total	**99.898**	**251.842**	**148.291**	**68.737**	**568.769**

Source: (Ministerio de Agricultura y Desarrollo Rural, 2019)

MATERIALS AND METHODOLOGY

The forest species Gmelina arborea Roxb belongs to the Verbenaceae family which presents fast growth. It is a deciduous species in dry areas. It can reach 30 m in height and grow to more than 80 cm in diameter. It usually grows with a clean shaft of 6 to 9 m and with a conical crown, wide in open places, but in plantations, its crown is dense and compact (Rojas Rodríguez *et al.*, 2004). It is one of the species with high yield potential and among the ten forest species with the greatest commercial influence in the country. This is especially due to advances in silvicultural management and genetic improvement. The great advantage of this species lies in its rapid growth and its strength to withstand severe periods of drought, without its quality for the furniture industry being diminished (Onyekwelu *et al*., 2003). The methodology of this study has four sequential phases (Figure 4).

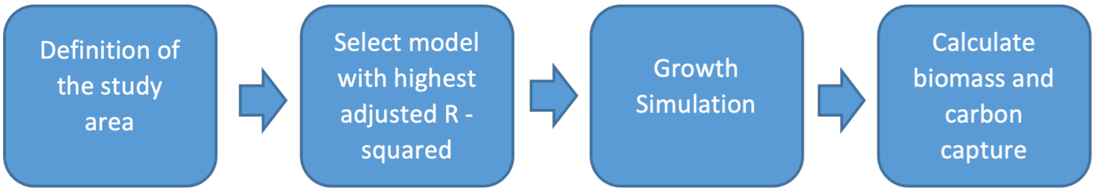

Figure 4. Description of the methodology.

Study area

The study was conducted with information from plots located in the region of Tolima, in the municipalities of Armero Guayabal (grounds of the University of Tolima, Granja de Armero: Centro Universitario Regional del Norte - CURDN), Coello (Finca El Neme), and Guamo (Finca Arizona, the Bellavista path).

The data used in this work come from 4 periodic measurements on 31 permanent sampling plots of the Gmelina arborea Roxb. species, which are part of the set of monitoring plots on the growth and yield of the promising species in the region of Tolima.

The sowing date of the plantations oscillates between the years 1997 and 2008.

For the study, measurements taken between the years 2009 to 2015 were considered, including coordinates of each of the trees. In this way, spatial information was available to help calculate the distance-dependent competence indices.

The circular plots installed have areas of 0.05 and 0.08 ha, with radii 12.5 and 16m respectively, which are on flat land.

31 plots containing a total of 5802 trees measured in the study area were measured four times. The variables measured were age (years), stem quality, stratification, angle and distance of the trees in the circular plots, normal diameter (at 1,30 m height), total height, commercial height, and in the last measurement, crown radius. The following were calculated: number of trees per hectare, basal area per hectare, mean square diameter, dominant height, and site index.

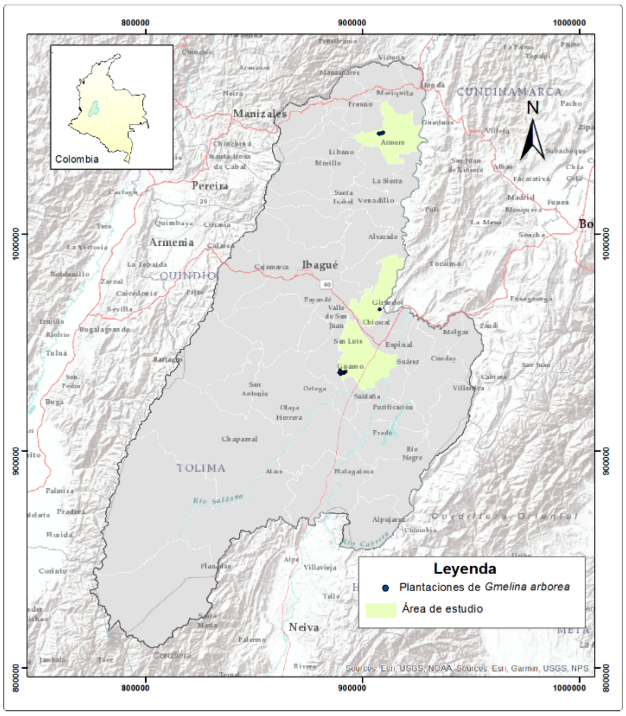

Figure 5. Municipalities with Gmelina arborea Roxb plantations in the region of Tolima which were part of this study.

Source: University of Tolima.

	Age	**DN**	**HT**	**HC**	**IS**
count	2649	2649	2649	2649	2649
mean	6,04977	14,80409	12,28924	6,37487	21,14
std	3,47227	6,07392	5,58264	3,70966	2,33
min	1,46	1,6	2,07	0	16,03
25 %	3,21	10,4	7,8	3,48	19,20
50 %	4,9	13,9	10,7	5,04	21,50
75 %	8,15	18,7	16,8	9,45	23,00
max	16,29	45,1	42	41	24,60

Table 3. Summary of tree and mass variables in the last measurement.

Legend: DN: normal diameter (cm), HT: total height (m), IS: Site index, HC: canopy height (m), Age: age (years).

Normal section models:

Using the field measurements of the permanent plots, a normal section growth model can be created to model the plantation (CONIF, 2011).

The growth of a tree does not only depend on the species or quality of the seed, there are many factors that can affect or stimulate the growth of the plantation: quality of the site, age of the tree, density, and intensity of the competition exerted by the trees that surround it for resources such as water, light, and nutrients (Álvarez-Taboada, Barrio-Anta, Gorgoso Varela, & Álvarez-González, 2003).

Therefore, an individual tree diameter growth model must take all these factors into account. For this reason, three linear models were proposed that incorporate the variables measured in the field: age, normal diameter, number of trees, the calculation of the site index from the measured heights, and the projection of the density per hectare.

The first model includes age (t), diameter (d), and site index (SI) to calculate diameter growth (delta diameter - ΔD). (Equation (1)).

$$\Delta D = a_1 + a_2 \cdot t + a_3 \cdot d + a_4 \cdot \mathrm{IS} \tag{1}$$

The second model includes the period between measurements (Δt), through which the diameter delta was calculated. (Equation (2).

$$\Delta D = a_1 + a_2 \cdot t + a_3 \Delta t + a_4 \cdot d + a_5 \cdot \mathrm{IS} \tag{2}$$

The third model includes the natural logarithm of the measured and calculated variables (Álvarez-Taboada *et al.*, 2003). (Equation (3)):

$$Ln(\Delta D) = a_1 + a_2 {\cdot} Ln(t) + a_3 Ln(\ \Delta t) + a_4 {\cdot} Ln(d) + a_5 {\cdot} Ln(IS) \tag{3}$$

Equation for modeling:

$$Ln(\Delta D) = a_1 + a_2 {\cdot} Ln(t) + a_3 Ln(d) \tag{4}$$

Growth simulation:

According to Peng (2000) two basic approaches have been used for modelling forest growth: an empirical approach with which the yield and growth of forest plantations are modeled and a mechanistic approach such as process models.

In this work, the empirical approach will be used to build the models and the simulation. For the simulation, the initial diameters were generated based on the distribution found in the plots of one year according to the stratification (sociological position) made during the measurement. The height is calculated with Equation (5), parameterized by multiple linear regression, from the data of age and diameter of the tree, obtained in the measurements.

$$Ln(HT) \; = \; a_1 \; + \; a_2 \bullet Ln(Ed) \; + \; a_3 \bullet Ln(\; DN) \tag{5}$$

Where HT - total height, Ed- age, DN- normal diameter, ai- parameters to adjust.

As the objective of the simulation (Fransson *et al.*, 2020) is to determine the diameter and volume of wood at the time of final harvest, as well as the equivalent carbon sequestration in biomass, the maximum density that a stand can reach before thinning (Gezan *et al.*, 2007) is a restriction, which is achieved by comparing the SDI value (Equation (6)) with the SDI$_{max}$ (Equation (7)). To comply with the restrictions at the time of modeling, the year and intensity of two thinnings before total harvesting must be taken as parameters (Kuehne *et al.*, 2022).

In the current study case, the index chosen is the density index, which employs the variables: number of trees per hectare N, mean square diameter of the plantation Dg, and a constant "b"defined by Reineke in 1933, with a value of -1,605 for several species. The index thus corresponds to the number of trees per hectare that a specific stand could reach if its average square diameter was 25 cm, as expressed in Equation (6) (Arias Aguilar, 2004).

$$\mathbf{SDI}= \mathrm{N}*\left(\frac{25}{\mathrm{Dg}}\right)^{\mathrm{b}} \tag{6}$$

The maximum value of the Stand Density Index (SDI$_{max}$), indicating the maximum level of competition, and thus frequently used as an indicator of the stand's upper load limit, can be obtained (Navarro Cárcamo *et al.*, 2011). Equation (7):

$$\mathbf{SDI_{max}}= 10^{\mathrm{a_{Máx}}} * 25^{\mathrm{b}} \tag{7}$$

These indices will be calculated in a Python script and considered as constraints in the simulation.

According to the results obtained in the work of Ramos and Niño (2017) to calculate the volume of the tree, the equation formulated by Schumacher and Hall (1933) was the model with the best results:

$$v = \beta_1 * d^{\beta_2} * H^{\beta_3} - e \tag{8}$$

The simulation includes the calculation of: section area of each tree at breast height from the Normal Diameter given in meters (DN/100) - A (Equation (9)), the basal area of the plot - G (Equation (10)), where n is the number of trees in the plot), number of trees per hectare - N (Equation (11), where a_p is the area of the plot) and the quadratic mean diameter - d (Equation (12)):

$$A = \pi * \left(\frac{DN}{100 * 2}\right)^2 \tag{9}$$

$$G = \sum_{i=1}^{n} A \tag{10}$$

$$N = \frac{10000}{a_p} \sum_{i=1}^{n} 1 \tag{11}$$

$$d = \sqrt{\frac{40000 * G}{\pi * N}} \tag{12}$$

Carbon study

The weight or equivalent estimate of organic matter that exists in each forest ecosystem above and below ground is called forest biomass (Obando Bonilla, 2004). In this definition, it is understood that the ecosystem under study is the tree, which is subdivided for the purposes of biomass calculations into: stem mass, branches, leaves, bark, roots, litter, and dead wood; percentage shown in Table 4. The total biomass for that year (Martins Silva *et al.*, 2019; Obando Bonilla, 2004) and their respective carbon capture (Rodriguez Santos, 2013), have to be periodically calculated. It is normally quantified in tons per hectare of green or dry weight. The biomass of the total tree is composed of the Below-ground Biomass and Aerial Biomass. The underground biomass is made up of the roots of the tree and the aerial biomass is made up of the biomass of the stem together with the biomass of branches, leaves, flowers, and fruits.

Two relationships used to calculate the total biomass: Biomass expansion factor (FEB)

$$FEB = \ AERIAL\ BIOMASS/\text{TRUNK BIOMASS} \tag{13}$$

And the ratio R between ground biomass and aboveground biomass

$$R = \ \text{GROUND BIOMASS/AERIAL BIOMASS} \tag{14}$$

For the calculation of the aerial biomass in the plantations of the tropical dry forests of the Department of Tolima, the following equation is used (Rodriguez Santos, 2013):

$$Log_{10}(B) \ = \ a_1 \ + \ a_2 \bullet Log_{10}(DAP) \tag{15}$$

Along with the following a_1 parameters = -1,988 $\pm$ 0,192, a_2 = 2,993 $\pm$ 0,138.

Determination coefficient R^2 = 0,97 y CME=0,070.

Thus, based on the study by Rodríguez Santos (2013), tree diameter can be related to biomass.

Likewise, the following distribution is obtained for this region (Obando Bonilla, 2004):

COMPONENT	CARBON %	BIOMASS %
Stem	43,13	63,87
Branches	41,39	16,35
Thin Root	41,75	4,38
Thick Root	42,55	12,43
Leaves	36,46	3,27
AVERAGE	**41,39**	**100**

Table 4. Percentage of average carbon by component and percentage that the component constitutes of the total biomass of *Gmelina arborea* Roxb trees.

To calculate the carbon captured or stored, the following relationship is used for the species:

$$CA = B \bullet FC\,(44/12) \tag{16}$$

where: CA is the stored CO_2, B is the biomass (underground, aerial or total) of the tree and FC are the carbon fraction for the species calculated at 42,497 (See Table 9).

RESULTS AND DISCUSSION

According to the equations suggested above, this section presents the results of the adjusted parameters through multivariable regression.

Variable	Parameter	coef	std err	t	P>|t|	R^2	R^2 adjusted
Const	a_1	3,260	0,239	13,610	0,000	0,206	0.205
AGE	a_2	-0,232	0,011	-21,607	0,000		
DN	a_3	0,030	0,006	4,694	0,000		
IS	a_4	-0,042	0,011	-3,634	0,000		

Table 5. Results of the adjustment of the basic model of growth in section (Equation (1))

The results obtained in Table 5 show that this equation does not efficiently model tree diameter growth as shown by the R^2 and the adjusted R^2. Since the diameter increase is being calculated and the periods between measurements are not equal, it was necessary to introduce the time difference between these measurements as an independent variable of the model.

Variable	Parameter	coef	std err	t	P>|t|	R^2	R^2 adjusted
Const	a_1	2,892	0,251	11,510	0.000	0.358	0.357
AGE	a_2	-0,270	0,011	-23,892	0.000		
DeltaAGE	a_3	0,674	0,029	23,267	0.000		
DN	a_4	0,063	0,007	9,240	0.000		
IS	a_5	-0,068	0,012	-5,717	0.000		

Table 6. Results of the adjustment of the model of growth in section (Equation (2))

This parameter is included in Equation (2) as shown in Table 6.

The previous models are valid because they work in the period of growth of the trees in the stand. The value of the R^2 and adjusted R^2 statistics show that Equation (2) represents the model better than Equation (1), although their values are not as expected. However, as growth behavior is not linear, a third model is implemented by changing the measured values by their natural logarithm.

Variable	Parameter	coef	std err	t	P>|t|	R^2	R^2 adjusted
Const	a_1	4,471	0,510	8,770	0.000	0.454	0.453
Ln(AGE)	a_2	-1,741	0,045	-38,232	0.000		
Ln(DeltaAGE)	a_3	0,717	0,032	22,102	0.000		
Ln(DN)	a_4	0,894	0,063	14,221	0.000		
Ln(IS)	a_5	-1,369	0,174	-7,881	0.000		

Table 7. Results of the adjustment of the model of growth in section (Equation (3))

Again, the statistics of Equation 3 exceed those obtained in Equation 2. However, it was expected that they would exceed the value 0.5 in the adjusted R2. Since this was not obtained, an analysis was made of the data with respect to those outliers that could influence the results obtained. As a result of the analysis, the data that were outside the confidence intervals were excluded, reducing the data by 20 %. This is justifiable due to the irregular nature of the terrain, for example, trees that are close to water sources, and that continue to grow in periods of drought, unlike normal behavior, or those that are in shallow soils or on slopes where soil nutrients are scarce. With the new values, the following results are obtained:

Variable	Parameter	coef	std err	t	P>|t|	R^2	R^2 adjusted
Const	a_1	2,796	0,194	14,416	0,000	0,366	0.365
AGE	a_2	-0,233	0,009	-25,708	0,000		
DN	a_3	0,013	0,005	2,538	0,011		
IS	a_4	-0,014	0,009	-1,441	0,150		

Table 8. Results of the adjustment of the basic model of growth in section (Equation (1))

During the analysis and simulation, the following was established: since the simulation is done annually and the logarithm of this periodicity would give 0. Given that the delta of the diameter with respect to age is what needs to be found, the natural logarithm of this ratio (DeltaD/DeltaAGE) was quantified. And, in this sense, Equation (3) was operated with the new data.

Variable	Parameter	coef	std err	t	P>|t|	R^2	R^2 adjusted
Const	a_1	2,716	0,289	9,398	0.000	0.633	0.633
Ln(AGE)	a_2	-1,266	0,026	-49,188	0.000		
Ln(DN)	a_3	0,347	0,035	9,825	0.000		
Ln(IS)	a_4	-0,525	0,100	-5,225	0.000		

Table 9. Results of the adjustment of the model of growth in section (Equation (2))

In the simulation process, it is also evident that when representing a stand of one hectare, the site index does not vary. Therefore, it was analyzed to exclude it from the model according to equation (4), the results of the statistics show a non-significant difference of the R^2 adjusted with respect to Equation (3) (See Table 9 and Table 10).

Equation (5) was implemented to calculate the heights, and adjustments were made to the parameters shown in Table 11.

Biomass calculation

For the calculation of biomass, Obando Bonilla´s reseach (2004) on the same species in the North of Tolima was considered.

Variable	Parameter	coef	std err	t	P>|t|	R^2	R^2 adjusted
Const	a_1	1,246	0,067	18,589	0.000	0.628	0.628
Ln(AGE)	a_2	-1,221	0,024	-49,940	0.000		
Ln(DN)	a_3	0,271	0,032	8,368	0.000		

Table 10. Results of the height calculation adjustment (Equation (5)).

variable	Parameter	coef	std err	t	P>|t|	R^2	R^2 adjusted
Ln(const)	a_1	0,155	0,013	11,815	0,000	0,874	0,874
Ln(AGE)	a_2	0,299	0,005	59,885	0,000		
Ln(DN)	a_3	0,676	0,007	104,858	0,000		

Table 11. Results of the adjustment of the model of growth in section (Equation (4))

	FC	Biomass	Average	Root	Area
Stem	43,13	63,87	2754,7131		63,87
Branches	41,39	16,35	676,7265		16,35
Thin Root	41,75	4,38	182,865	4,38	
Thick Root	42,55	12,43	528,8965	12,43	
Leaves	36,46	3,27	119,2242		3,27
	41,056	100,3	4262,4253	16,81	83,49
		FC =	42,497	R =	0,20134148

Table 12. Biomass factor calculation

From the field measurements of one-year-old trees in the permanent plots, their mean and standard deviation were calculated. Based on these data the diameter values were randomly generated for the simulation of 1089 trees, equivalent to the approximate number of trees that fit in a stand of one hectare planted at 3 meters. In this way, the simulation is made from the given equations of volume (Equation (8)), height (Equation (5)), basal area of the tree (Equation (9)), biomass (Equation (11)), carbon capture and CO_2 equivalent (Equation (12)), diameter growth (Equation (4)) for each tree. With these data the basal area of the hectare G (Equation (10)), root mean square diameter d (Equation (12)), SDI (Equation (6)) are generated. The simulation is done at 12 years and includes a thinning in year 3 and year 5 with an intensity of 40 %, as shown in Table 13. The simulation was created using Python.

Age	G (mt^2/ha)	N (Number of tress)	d (Cms)	SDI	V (mt^3/ha)	CO_2_ha (Ton)
1	1,8214	1058	4,6818	37,7951	4,4681	2,3024
2	3,5888	1058	6,5719	74,1937	29,2202	19,8920
3	7,4069	1058	9,4413	152,5169	56,8395	40,9574
4	12,4554	899	13,2817	255,5116	82,8446	60,6567
5	18,2713	899	16,0865	374,0306	75,7326	57,6574
6	14,8875	494	19,5885	304,1003	90,9509	68,9885
7	17,5289	494	21,2554	357,7343	69,1763	53,4572
8	18,5667	469	22,4510	378,6848	77,6879	59,5823
9	17,3360	399	23,5203	353,4036	85,6810	65,1962
10	18,2749	399	24,1488	372,4345	93,2272	70,3775
11	18,6980	399	24,4268	381,0582	100,3835	75,1881
12	19,1260	399	24,7047	389,6819	107,1964	79,6778

Table 13. Simulation results for the species in twelve years including two thinnings.

The results are shown graphically (Figures 6, 7, 8, and 9):

Figure 6. Diameter growth

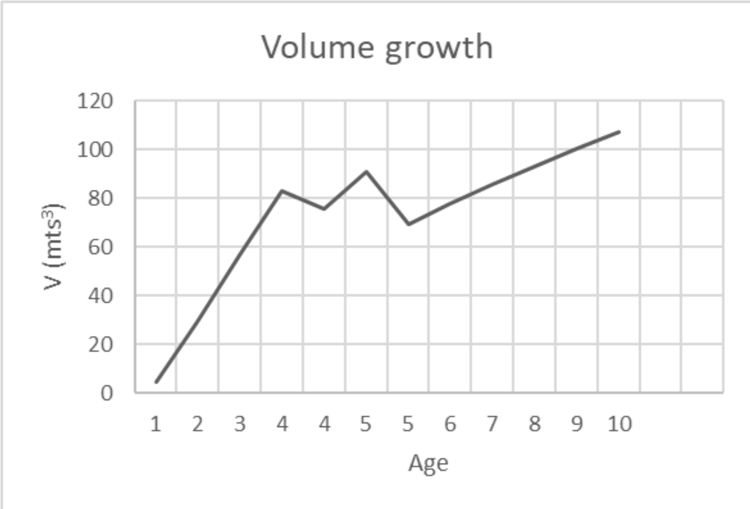

Figure 7. Volumen growth

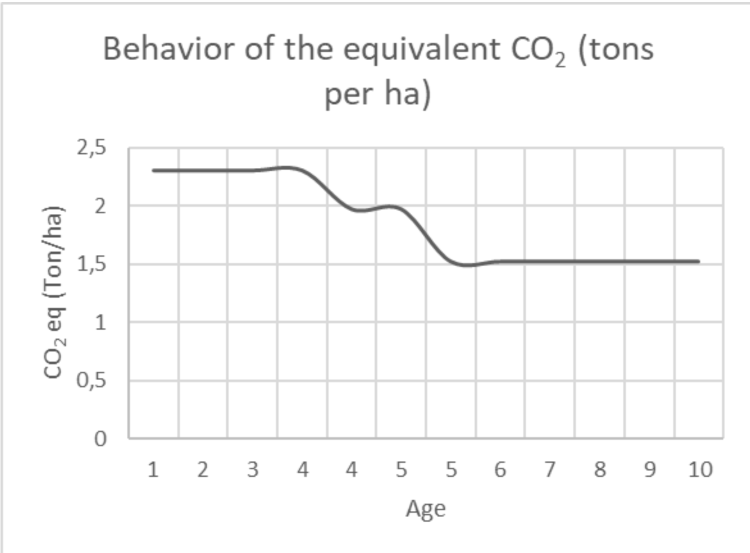

Figure 8. Behavior of the equivalent CO_2 (tons per ha)

CONCLUSIONS

Following the methodology described, it was possible to achieve the proposed objective, as the growth of the stand was simulated and at the same time the carbon captured for each period (one year) was calculated for the species Gmelina arborea Roxb. Although the adjusted growth model did not obtain a high Coefficient of Determination R^2 in the adjustment of the parameters, a accurate simulation was achieved.

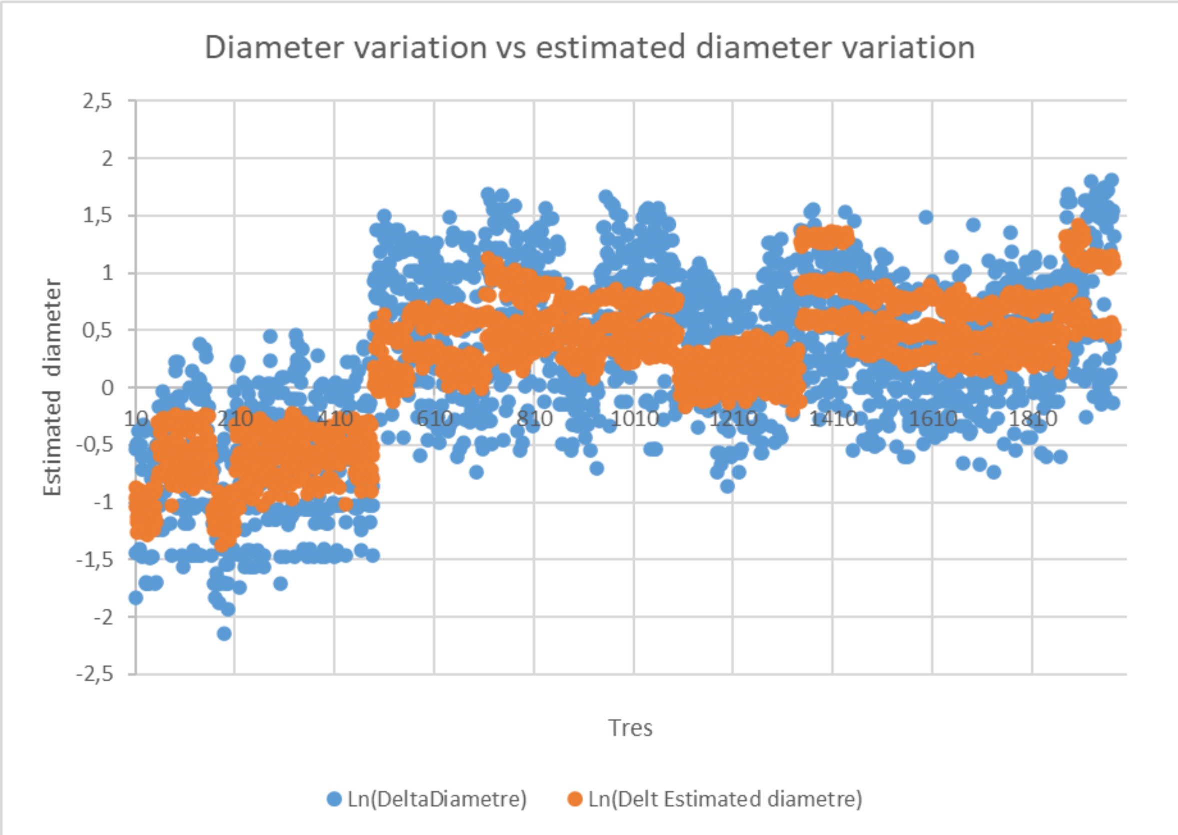

Figure 9. Diameter variation vs estimated diameter variation

The Gmelina is a promising species due to its rapid growth, behavior under competitive conditions, and extended use in the furniture and construction industries, as well as its contribution to mitigating natural forests and carbon sequestration.

Future research may include in the growth simulation process the explicit effect of silvicultural operations such as thinning and pruning, due to its important impact on the growth process when trees are overly sensitive to light and compete for limited resources.

In the same vein, future research can benefit from using computational intelligence techniques in growth models for forestry, as they allow addressing the non-linearity and recursiveness inherent in these processes. When indicators associated with competition between trees are included, these techniques can effectively capture their impact on growth, which is inherently conditioned by such factors..

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