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Determination of the amount of carbon in the aboveground biomass and soil in a teak plantation (*Tectona grandis* L. f.) of different ages in the canton of Santa Rosa, Ecuador

Determinación de la cantidad de carbono en la biomasa aérea y el suelo en una plantación de teca (*Tectona grandis* L. f.) de diferentes edades en el cantón Santa Rosa, Ecuador

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Abstract: Carbon capture by forest resources contributes to economic, social and environmental benefits, according to ssfsende. The objective of this study was to determine carbon capture in above-ground biomass and soil in a teak plantation (Tectona grandis L. f) of different ages in the Santa Rosa canton. Four ages were selected: 4, 8, 12, and 16 years. Four 20 x 25 m plots were established for each age. The variables studied were: DBH, total height, commercial height, seed biomass, fine necromass biomass, coarse necromass, and soil sample. Allometric equations were applied. At 16 years of age, a teak plantation can achieve a DBH of 30.40 cm, a height of 18.01 m, a commercial volume of 180 m3 ha-1 and a total volume of 260.79 m3 ha-1. Carbon sequestration in above-ground biomass at 16 years was a total of 115 tha-1 and carbon sequestration in the soil was 34.16 tha-1 . This study provides valuable information on carbon sequestration at different ages and the sustainable management of forest resources in T. grandis plantations, emphasising the need for continuous monitoring of plant diversity and carbon storage.

Keywords: Biomass, soil, aerial, carbon, volume.

Resumen La captura de carbono que realizan los recursos forestales contribuye obtener beneficios económicos, sociales y ambientales, por ssfsende, en el objetivo de este estudio se planteó determinar la captura de carbono en la biomasa aérea y el suelo en una plantación de teca (Tectona grandis L. f) en diferentes edades en el cantón Santa Rosa. Se seleccionaron cuatro edades de 4, 8, 12, y 16 años y se realizaron cuatro parcelas de 20 x 25 m por cada edad, las variables estudiadas fueron: dap, altura total, altura comercial, biomasa semillas, biomasa de materia necromasa fina, materia necromasa gruesa, muestra de suelo, se aplicaron ecuaciones alométricas. A los 16 años en una plantación de teca se puede obtener un dap de 30.40 cm, 18.01 m alto, un volumen comercial de 180 m3 ha-1 y un volumen total de 260.79 m3 ha-1, la captura de carbono en la biomasa aérea a los 16 años fue de un total de 115 tha-1 y una captura de carbono en el suelo de 34.16 tha-1. Este estudio proporciona información valiosa en la captura de carbono en diferentes edades y el manejo sostenible de los recursos forestales en plantaciones de T. grandis, enfatizando la necesidad de monitorear continuamente la diversidad vegetal y el almacenamiento de carbono.

Palabras clave: Biomasa, suelo, aéreo, carbono, volumen.

Introduction

According to Chisag (2015:10), "The diversity of ecological environments in Ecuador contributes to an exceptionally rich and varied flora, with approximately twenty-two thousand different plant species." Forests play a fundamental role as the main generators of organic matter. According to Andi (2015), during the process of photosynthesis, they absorb carbon dioxide (CO_2) present in the atmosphere and mix it with minerals, chlorophyll and water. Using solar energy through chemical reactions, they are converted into sugars and carbohydrates, and as a result of this process, oxygen (O_2) is released into the environment. The net retention of organic carbon in forests is conditioned by the way the vegetation cover is managed, the age of the trees, the size distribution, and the structure and composition of the forest ecosystem. These forests also play a key role in reducing the concentration of carbon in the atmosphere, which increases as a result of emissions generated by human activity. (Aguirre and Quizhpe, 2018).

Forests fulfil four fundamental functions in relation to climate change, as designated by the FAO (2012). Firstly, when they are cut down, overexploited or degraded, secondly, forests are sensitive to climate variations. Thirdly, when managed sustainably, and finally, forests have the potential to absorb around one-tenth of the global carbon emissions predicted for the first half of this century.

In the 21st century, climate change associated with potential temperature increases is one of the most severe environmental

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problems. According to Benjamin and Masera (2018:20), "the rapid increase in greenhouse gas emissions and the difficulties in substantially reducing this increase are the causes of environmental problems. They also point out that deforestation increases the amount of CEI annually."

According to Harris *et al*. (2011), it originated when the carbon cycle and its balance were disrupted. The solution must be considered in terms of reducing anthropogenic$_{CO_2}$ emissions and increasing carbon absorption. More than 650 billion tonnes of carbon are stored by forests worldwide, while deforestation, according to a report presented by CIIFEEN (2021:14), "accounts for 17.5% of global anthropogenic greenhouse gas emissions".

For the FAO (2918) and Michel (2019), taking action on this under the Kyoto Protocol or other treaties has not only led to significant changes in soil management, but has also increased the organic matter content of the soil, having a positive impact on the environmental qualities of the ecosystem, in contrast to the agricultural expansion taking place in Latin America with its pressure on these natural resources.

In Ecuador, according to the Ministry of Energy and Mines (2022), there is a National Climate Change Strategy that came into force at the end of the same year, which aimed to create favourable conditions for the adoption of measures to reduce GHGs and increase carbon sinks in strategic sectors, with the forestry sector being a very important productive activity for maintaining and strengthening mitigation initiatives.

To determine the carbon content in the sector's forest plantations, according to the Ministry of the Environment (2023:10), "it is mainly necessary to know how much these types of ecosystems store, in order to determine the annual accumulation rate and generate updated projections."

Among the tropical forest species in the country, teak has gained large areas of land covering nearly 30,000 ha, and as stated by Fonseca (2018), "it has important characteristics for its use in climate change mitigation: its study is important in terms of carbon capture and its environmental benefits until harvest."

It is therefore of great interest to generate greater knowledge about the benefits of timber forest species, not only in the economic sphere, but also in order to promote climate change mitigation initiatives.

In the Santa Rosa canton of the Province of El Oro, MAG has encouraged the production of raw materials to supply the timber industry and contribute to reducing the indiscriminate exploitation of native forests. According to this information, around 80 hectares of teak were planted with the aim of obtaining good economic results after 15 years, with profits that could range from $200,000 per hectare. This consists of reimbursing up to 75% of the costs of establishing and maintaining a plantation (Semplades, 2017).

Methodology

The research was carried out in the parish of Jumon, in the canton of Santa Rosa ( ), in the province of El Oro. The Santa Elena forest plantation belongs to the Reybanpac Company, with a total area of 310 hectares, with T. grandis being the most predominant species with 187 hectares distributed across 15 plots of different ages. Four plots were selected for the study, with a difference of four years between each one (4, 8, 12 and 16 years).

Rectangular plots measuring 20x25 m (500 m²) were used as sampling units.2). Within each plot, the DBH (diameter at breast height) was measured and the height of each tree was estimated. The tree with the largest and smallest DBH and height was selected to obtain samples of FNM (fine necrotic matter), GNM (coarse necrotic matter) and seeds in a m2 . In the centre of each plot, a 1 m2 pit was dug to determine the amount of carbon stored in the soil, Figure 1 and Table 1 (Schelegel, 2001).

Table 1. *Description of the division of the sampling unit.*

#	Name	Dimension	Parameters
1	Sampling unit	20x25 m	Measurement of DBH and H / Evaluation of average tree
2	Plots	1x1 m	Evaluation of fine deadwood
3	Plots	1x1 m	Assessment of coarse dead organic matter
4	Test pits	1x1 m	Soil samples

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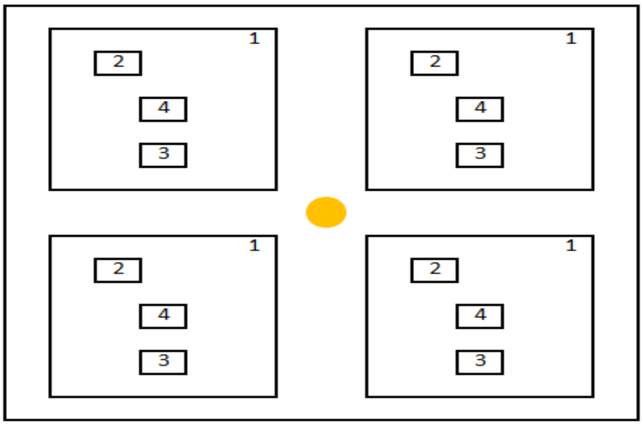

Figure 1. Sampling unit.

Dasometric calculations

Densimetric calculations were used to determine the volume stored in the study area, as well as to calculate the carbon stored (Ruiz-Blandon et al., 2020).

-Diameter: The diameter was recorded at 1.30 m from the base of the tree using a diameter tape

-Total height: Height was measured in metres using an altimeter, considering a distance of 15 m to measure the total height.

-Basal area: Once the diameter data had been obtained, the basal area (m^2) of each tree was calculated using the following formula.

BA = π* (D)^2/4

Where:

BA = Basal area in m2

Π = 3.1416

DAP2 = Diameter squared in centimetres

-Volume: Data on basal area and total height were used to calculate volume (m^3). For each tree, the following formula was applied.

V = AB * h * f

Where:

V = volume (m^3)

AB = basal area (m^2)

h = stem height (m)

f = form factor (0.7)

-Average annual increment (AAI): Data from the study variable (dasometric) was used and divided by the age of the plantation using the following formula.

MAI = (tree volume) / (E)

Where:

AGI = annual growth index

Tree volume = tree volume

E= tree age

Determination of carbon in fine, coarse and seed deadwood

To determine coarse deadwood, a 1x1 m (1 m^2) plot was established at the four sampling points, where all coarse deadwood was collected: branches larger than 2 cm in diameter found on the ground. For fine necromass, leaf litter and branches smaller than 2 cm were collected, and in the case of seeds, all material was collected. The material obtained from the plots was then weighed, placed in labelled transparent plastic bags and taken to the Biotechnology Laboratory.

These samples were cut into small portions until 100 g was obtained and placed in a paper bag with their respective identification. They were then weighed on a Trooper OHAUS analytical balance, recording the wet weight, and dried in a Memmert oven with forced air circulation for 72 hours at 60 ºC (González, 2018). The following formula was applied:

Bm= (Phx%MS) /100

Where:

Bm= biomass (coarse, fine, seeds)

Ph= wet weight of material

%DM = percentage of dry matter

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To determine the amount of carbon in the above-ground biomass, the values obtained from the samples taken to the laboratory were used according to the carbon percentages. Carbon was determined using the Schollemberger method.

Cba = Cmnf + Cmng + Cs

Where:

Cmnf = carbon in fine necrotic matter

Cmng = carbon in coarse necrotic matter

Cs = carbon in seeds

Carbon sequestration in the soil in T. grandis plantations

Boreholes were drilled in each of the sampling plots to a depth of 60 cm. They were located in the centre of the plot and divided into three levels: 0–20 cm; 20–40 cm; and 40–60 cm. At each level, approximately 2 kg of soil samples were taken, placed in labelled transparent plastic bags, and taken to the Biotechnology Laboratory. These samples were placed in paper bags with their respective identification, weighed until 100 g was obtained on the Trooper OHAUS analytical balance, recording the wet weight, and dried in a Memmert oven with forced air circulation for 72 hours at 60 ºC (González, 2022).

Once dry, the material was left to cool for 30 minutes and then weighed to determine the dry matter percentage. This material was then ground using a 4-E Grinding Mill electric mill, and 100 g was placed in labelled plastic bags and stored in a dry place until its active organic carbon analysis, which will be carried out at the INIAP at the Pichilingue Tropical Experimental Station (González, 2022). The bulk density (Db) will be obtained directly from the dry mass weight and the cylinder volume (González, 2022).

Db=Mss/Vc

Where:

Db = Bulk density in g/cc

Mss = Dry soil mass

In addition, the formula was applied to obtain the amount of carbon stored:

Ca = PcxDaxP

Where:

Ca = active organic carbon stored

Pc= active organic carbon in the soil (%)

Da= bulk density (g/cm^3)

P= soil depth (cm)

Carbon profitability in a T. grandis plantation

To determine the economic valuation of carbon, the total economic valuation (TEV) was considered, taking into account direct use values, where investments, costs and revenues were established.

Internal rate of return:

IRR=TM+(TM-Tm)((NPV tm)/(NPV Tm-NPV TM))

Where:

IRR = internal rate of return

Tm= lower interest rate

IRR= higher interest rate

NPV = net present value of the lower rate

NPVMA = net present value of the higher rate

Net present value:

NPV = -I + (FNE 1)/((1+i)) + (FNE 2)/(1+i)^2 + (FNE 3)/(1+i)^3 + (FNE n+vs)/(1+i)^n

Where:

NPV = net present value

I= investment

NCF = net cash flow

(i)= discount rate

(n)= number of periods

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VS = salvage value, residual value or redemption value

Benefit-cost ratio:

B/C ratio = (net benefit)/(total cost)

The cost per metric tonne of carbon stored for forest species, including primary and secondary forests, agroforestry systems and plantations, according to the World Bank for the years 2020 to 2030, will average \$38.53 Tm-1 and is expected to increase in the coming years due to the demand for environmental projects in developing countries.

Results

Densimetric variables and IMA at different ages in a T. grandis plantation

The dasometric variables show growth ranging from 13.42 cm dap in plot one to 30.40 cm in plot four. In the total height variable, growth was 8.34 m for plot one, reaching 18.01 m in plot four. The basal area ranged from 8.70 m2ha-1to 20.69 m2ha-1, and total volume growth ranged from 50.78 m3 ha-1for plot one to 260.79 m3ha-1for plot four (Table 3).

Meanwhile, in terms of the average annual increase (AAI), the growth values in DBH ranged from 3.35 cm in plot one to 1.9 cm in plot four, while in total height they ranged from 2.08 m to 1.12 m, and in basal area from 0.54 m2ha-1to 0.08 m2ha-1, and total volume initially increased from 12.69 m3ha-1to 16.29 m3ha-1in 16 years (Table 4).

Table 2. Dasometric variables of T. grandis at different ages.

Lot	Age	Diameter	Height Com.	Total height	Base area	Com. Vol.	Total volume
		(cm)	(m)	(m)	(m^2 /ha^{-1})	(m^3/ha^{-1})	(m^3/ha^{-1})
1	4	13.42	2.2	8.34	8.70	13.40	50.78
2	8	18.00	5.13	11.64	13.11	36.10	116.78
3	12	23.45	8.95	15.92	17.06	139.35	190.11
4	16	30.40	12.45	18.01	20.69	180.28	260.79
Average		21.32	7.18	13.48	14.89	92.28	154.62
C.V. (%)		0.34	0.62	0.32	0.35	0.87	0.59

Table 3. IMA of *T. grandis* at different ages.

Batch	Age	Diameter	Height Com	Total height	Basal Area	Com Vol.	Total Vol.
		(cm)	(m)	(m)	(m^2 /ha^{-1})	($m^{3/ha^{-1}}$)	($m^{3/ha^{-1}}$)
1	4	3.35	0.55	2.08	2.17	3.34	12.69
2	8	2.25	0.64	1.45	1.64	4.51	13.34
3	12	1.95	0.74	1.32	1.42	11.61	15.84
4	16	1.9	0.77	1.12	1.29	11.26	16.29
Average		2.36	0.68	1.50	1.63	7.79	14.55
C.V. (%)		0.29	0.15	0.28	0.24	0.57	0.12

Amount of carbon stored in above-ground biomass and soil in a T. grandis plantation

The carbon stored in above-ground biomass showed an increase in the variables of this study. In the case of seeds, fine and coarse necrotic matter, the data obtained in the 16-year-old plot in the T. grandis plantation were 1.32 tha-1 ; 1.29 tha-1 ; 8.89 tha-1 respectively (Table 4).

Table 4. Carbon stored in necrotic biomass and seeds in the T. grandis plantation.

Plot	Age	Seed carbon (tha^{-1})	Mng carbon (tha^{-1})	Mng carbon (tha^{-1})
1	4	0.34	0.51	4.18
2	8	0.59	0.88	4.92
3	12	0.97	1.07	6.29
4	16	1.32	1.29	8.89
Average		0.80	0.94	6.07
C.V. (%)		1.87	2.83	2.93

The percentage of carbon represented by the capture between ages ranges from 5.03 tha-1 in plot one to 11.50 tha-1 in plot four (Table 5).

Table 5. Average carbon (%) in the T. grandis plantation.

Plot	Age	% Carbon in dead wood and seeds (tha^{-1})
1	4	5.03
2	8	6.39
3	12	8.32
4	16	11.50
Average		7.81
C.V. (%)		2.78

In short, as the plantation, forest or stand ages after planting, atmospheric carbon capture increases due to the amount of plant material it generates, such as leaf litter, seeds, twigs and forest residues, among others. In the case of the research, this ranged from 50.28 tha-1 for plot one to 115.02 tha-1 for plot four, as detailed below (Table 6).

Table 6. Total aerial carbon capture in the T. grandis plantation.

Plot	Age	Above-ground carbon (tha^{-1})
1	4	50.28
2	8	63.86
3	12	83.24
4	16	115.02
Average		78.10
C.V. (%)		2.78

In the case of soil carbon content, the percentage of carbon found among the different ages ranges from 1.56% in the fourth year to 1.70% in the 16th year (Table 7).

Table 7. Average carbon content (%) in the T. grandis plantation.

Plot	Age	% Carbon in soil
1	4	1.56
2	8	1.66
3	12	1.67
4	16	1.70
Average		1.64
C.V. (%)		27.11

Carbon sequestration in the soil depends on its depth, as evidenced by the data obtained, which shows a decrease in carbon as the soil becomes deeper. This results in an initial capture of 43.24 tha-1 between the initial 20 cm, reaching 23.34 tha-1 at a depth of 60 cm at 16 years of age (Table 8).

Table 8. Carbon sequestration based on soil depth in the T. grandis plantation.

Plot	Age	Soil carbon (tha^{-1})		
		0 to 20 cm	**20 to 40 cm**	**40 to 60 cm**
1	4	26.42	25.05	13.67
2	8	31.23	27.78	15.51
3	12	38.39	32.64	18.95
4	16	43.24	35.90	23.34

Average	34.82	30.34	17.87
C.V. (%)	4.67	6.25	4.20

Whereas soil carbon sequestration without surface stimulation can result in time-based growth, in the case of T. grandis, it was found that for the four-year plot, sequestration was 21.72 tha-1 and for the 16-year plot, sequestration was 34.16 tha-1 (Table 9).

Table 9. Soil carbon content in the T. grandis plantation.

Lot	Age	Soil carbon (tha^{-1})
1	4	21.72
2	8	24.84
3	12	29.99
4	16	34.16
Average		27.67
C.V. (%)		5.03

The carbon in the system comprises both the carbon values in the above-ground biomass and the carbon in the soil, between which it was determined that the amount of carbon stored by the T. grandis plantation after four years is 77.02 tha-1 and 160.69 tha-1 for 16 years (Table 10).

Table 10. Carbon in the system in the T. grandis plantation.

Plot	Age	System carbon (tha^{-1})
1	4	77.02
2	8	95.09
3	12	121.55
4	16	160.69
Average		113.59
C.V. (%)		3.13

Profitability of carbon capture in a T. grandis plantation

The profitability of the project within the plantation showed a cost of $1624.20 tha-1 , a net benefit of $2451.12 tha-1 and a net profitability index of $3.12 tm3 , making it beneficial to maintain this forest resource as an economic income source for carbon sequestration (Table 11).

Considering that economic benefits can be obtained until the forest is harvested, with a total of 25.14 ha distributed across the four study plots, carbon storage of 105.7 mt3ha-1and profitability of £3.12 mt3ha-1, the annual income will be £8,290.

Discussion

Of the dasometric variables according to studies conducted by Arias (2011) and UICYT (2006), agree with the data obtained for the diameter variable in the Santa Rosa canton with an age of 12 years, average of 23.45 cm, indicating that tree growth is influenced by environmental factors such as soil conditions, which are similar in the Quevedo and Balzar cantons. The total height values differed from those reported by Arias (2011) and UICYT (2006) but were consistent with those obtained by Rosas (2011) in his research in the canton of Quinindé, being similar to those obtained in Santa Rosa with a value of 11.64 m.

Likewise, the total height values are consistent with those obtained in the canton of Quinindé according to Rosas (2011), with an average of 15.92 m3, which is lower than that reported by UICYT (2006) and Arias (2011) in the Quevedo area.

In the Ecuadorian Amazon region, Villavicencio (2015) concluded that a six-year-old stand had a DBH of 16.70 cm and a height of 12 m, while in another study presented by Proaño (2007), determined that the values at five years of age are 10.74 cm and 9.71 m in height on the coast, while for the four-year-old plantation, the DBH data were 13.42 cm, which is within the data proposed by the authors, and an average height of 8.34 m, which is below the age of five years.

In the study conducted by Jiménez et al (2020), an 11-year-old plantation in Michoacán had an average DBH of 16.55 cm, which differed from that reported in plot two, where an eight-year-old plantation had a DBH of 18 cm. while the total height had an average of 13.01 m, which differs from the study, as an average height of 11.64 m was obtained. This is because the plantation in Mexico had a density of 1,666 trees ha-(1), meaning that the trees seek to grow in height due to competition for light.

Carbon in above-ground biomass grows based on the age of the plantation, since, according to studies by Brown et al (2019) and Arias (2011), it depends on the growth of the forest or plantation, as, like total volume, carbon increases with diameter and height.

The biomass content of the trunk, according to research carried out by Landeta (2009), shows that in a teak plantation, carbon content ranging from 7.40 tha-1 to 18.72 tha-1 for eight-year-old trees. This data differs from the research, as at the same age it presented a carbon content of 6.39 tha-(1) ,which is below the minimum.

According to research by Guarnizo and Palacios (2013), they determined that at four years of age, in the Loreto area, teak obtains a biomass of 66.12 tha-1 and stored carbon of 33.06 tha-1 , while the results in the Santa Rosa area are lower at 50.28 and 21.72 tha-1 respectively.

The average carbon content in soil depends on the type of soil and nutrient content that contribute to maintaining the amount of carbon stored in the soil. According to Ibrahim et al. (2019), the minimum values range from 43 tha-1, while in the study the maximum values were 34.16 tha-1 . On the other hand, the data obtained by Landeta et al (2009) show that the averages in an eight-year-old teak plantation were 24.28 tha-1 , which is consistent with the 24.83 tha-1 in the province of Santa Rosa.

In a study conducted by Jaramillo and Correa (2015) in the province of El Oro, they determined that in a 14-year-old plantation, carbon sequestration in the soil is 17.15 tha-1 . In Costa Rica, in Eco Bosques plantations, according to Quintero et al (2019), data ranging from 29.6 tha-1 at 12 years of age. This is consistent with the data obtained of 29.99 tha-1 for the same age, but differs from that obtained by Jiménez and Landeta (2020), since at eight years of age it shows a capture of 27.68 tha-1 , which differs from the research proposed by Reddy et al. (2014), who indicate that at the age of 15, carbon sequestration in a plantation in India was 108.53 tha-1

At eight years of age, the teak plantation had a soil carbon sequestration of 24.84 tha-1 , with values similar to those reported by Jiménez and Landeta (2020), with seeds from Brazil and Ecuador yielding a production in the country of 23.1 tha-1 and 25.56 tha-1 correspondingly.

According to González et al (2018), the deeper the soil, the less organic matter aggregates form, meaning less carbon. Similarly, it states that forest ecosystems are significant carbon reservoirs. These ecosystems harbour considerable amounts of carbon stored in biomass, both living and dead, as well as in the soil. Specifically, it points out that tropical regions, due to their size and rich biodiversity, play a crucial role as vast carbon deposits or sinks.

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Within the economic assessment of proposing carbon capture in above-ground biomass and soil as a source of income, Mora (2011) indicates that the economic income generated by the sale of timber is higher than the income generated by the sale of carbon certificates, but the valuation of teak assets shows that cultivation is profitable, feasible and viable, with 12%, which is consistent with the data obtained in the research, which showed a profitability of $3.12 mt3.

Conclusions

Among the dasometric variables, proportional growth was found in the different plots of the T. grandis species in the Santa Rosa Canton, starting with a diameter of 13.42 cm, total height of 8.34 m, basal area of 8.70 m^2 tha-1 and total volume of 50.78 m^3 tha-1 for the four-year-old plot, reaching a diameter of 30.40 cm, total height of 18.01 m, basal area of 20.69 m^2 tha-1 and total volume of 260.79 m^3 tha-1 for the 16-year-old plot. Carbon sequestration in above-ground biomass and soil for the four-year plot was 50.28 tha-1 and 21.72 tha-1 respectively, while at 16 years it achieved sequestration of 115.01 tha-1 and 34.16 tha-1 in the above-ground biomass and soil, respectively. The profitability of conducting carbon studies in the T. grandis plantation was $3.12 mt3, defining it as a beneficial project for the forestry economy.

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