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ESTIMATION OF BIOMASS, CARBON AND CO_2 OF *Khaya senegalensis* (DESR.) A. JUSS

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Abstract: The objective was to estimate biomass, carbon and carbon dioxide in plantations of: *Khaya senegalensis* A. JUSS, with 32 months of age, covering an area of 12.00 ha, in the southern region of the State of Tocantins. The direct method of quantification was used, installing 13 plots of 25 x 30 m, randomly distributed and 22 trees felled, according to the diametric class. Sample discs were taken from the base and middle of the trunk, weighed while still wet and dried in an oven at 70ºC to obtain the dry weight. 13 mathematical models were adjusted for biomass quantification. Carbon was calculated by multiplying the biomass result by 0.45 and converted into carbon dioxide using the conversion factor 3.67. The model employed showed:
Syx% de 5,94 e R^2aj de 0,93. The results found were 5.45 ton.ha-1 of biomass, 2,45 ton.ha^{-1} of carbon and 9,00 ton.ha^{-1} $_{of}$ carbon dioxide.
Keywords: African mahogany; carbon sequestration; direct method.

INTRODUCTION

With the relevant global concern with regard to climate change and environmental degradation, in 1997, in the city of Kyoto, during the Third United Nations Conference on Climate Change, the Kyoto Protocol was elaborated, which recognizes the need to a global effort to tackle climate issues (Morais, et al., 2017).

Aiming to find ways to reduce greenhouse gas emissions, especially carbon dioxide, the Kyoto Protocol presented alternative instruments so as not to affect world economic development (Júnior et al., 2013). Carbon sequestration emerges as an alternative to mitigate gas emissions into the atmosphere, is one of the greatest contributions in the process of curbing climate change, and is also an important ecosystem service provided by forests (Fajardo & Timofeiczyk, 2015).

Forests are important carbon accumulation zones, actively participating in the CO2 cycling process in the atmosphere, through natural or anthropogenic processes. About 50% of carbon is stored in forest biomass and 50% in soil (FAO, 2018).

Several studies emphasize the ability of forests to remove CO2 from the atmosphere, storing carbon in their biomass (Watzlawick et al., 2013). Afforestation and reforestation practices are the most common ways of absorbing or sequestering excess carbon in the atmosphere, since in the growth phase of trees, through the process of photosynthesis, they demand a large amount of carbon to develop (Nunes, 2014).

In this context, today forests planted with exotic species, such as: Pinus, Eucalyptus, Cedar, Teak, African mahogany, are also being implanted with a view to carbon sequestration. Exotic species such as African mahogany, have stood out for their growing cultivation in Brazil, showing fast growth when compared to other noble species, and easy adaptation. (Soranso et al., 2016). The *Khaya senegalensis* (Desr.) A. Juss., is a species of mahogany, which originated in countries on the west coast of the African continent, a region with edaphoclimatic characteristics similar to some regions of Brazil (Júnior et al., 2017).

Cultivation of the species in Brazil began as a substitute for native mahogany. (*Swietenia macrophylla* King). This was widespread and recommended mainly due to the great similarity between the species and the ban on the exploitation and commercialization of native mahogany (França et al., 2015). According to the Brazilian Association of African Mahogany Producers, in Brazil there are already approximately 10,000 hectares planted with mahogany in different states (Ribeiro et al., 2017).

The species: *Khaya senegalensis* is drought tolerant, supporting a period of 4 to 7 months of drought (Joker & Gaméné, 2003). Matos et al. (2016), emphasize that the species has moderate tolerance to water deficit. These conditions are found in the State of Tocantins, a region where the culture is being disseminated, due to the great silvicultural potential of the State. Boasting a promising capacity for crop development and consequently carbon storage, as the production of woody material is related to carbon sequestration (Missio et al., 2017) and its storage in the biomass, with the quantification of these parameters being of paramount importance.

Studies found in the literature use very similar and generalized methods and techniques to obtain carbon estimations. Therefore, all works are based on recurrence equations, regarding assumptions on the amount of carbonic biomass (Dias et al., 2015).

For the estimation of forest biomass and carbon, there are two commonly used methods, which can be the direct or indirect method, direct consists of weighing all the biomass usually by a destructive process and indirect implies the use of some type of biomass and carbon modeling, employing whether factors or equations. However, such factors or equations need to be adjusted to a primary database, to guarantee validity to the Estimations (Sanquetta et al., 2014).

This Forest Biomass Estimation can be done through the inventory of the vegetation through plots, application of appropriate allometric equations and the extrapolation of the results (Henry et al., 2010).

Based on this, this study aimed to estimate the biomass, the carbon stock and the accumulation of carbon dioxide, present in the aerial part of a forest plantation of *Khaya senegalensis*, in the south of the State of Tocantins, through the direct method, with the application of the forest inventory and the adjustment of the allometric equation for the area.

MATERIAL AND METHODS

CHARACTERIZATION OF THE STUDY AREA

The study was carried out at Fazenda Jarina, located in the municipality of Gurupi, Tocantins (Figure 1). The city is located in the south of the state, 214 km from Palmas, the state capital, and 596 km from Brasilia, the country's capital. The municipality is located on the watershed between the Araguaia River and the Tocantins River, on the banks of the BR-153, and covers an area of 1,836.091 km², with an estimated population for the year 2016 of 84,628 inhabitants (IBGE, 2017).

Fazenda Jarina is a rural property whose main activity is the cultivation of African mahogany. (*Khaya senegalensis*). The property has a total area equivalent to 70.77 ha.

The area studied on the property covers 12.00 ha, where the planting of: *Khaya senegalensis,* since December 2013, with spacing of 6 x 4 m, the seedlings used in planting are of seminal origin and there is no irrigation system on the property. At the time of data collection, the plantation was 32 months old.

Through the geographic database of the Planning and Budget Secretariat of the State of Tocantins, the regional climate, precipitation, temperature and soils found in the study area were characterized (SEPLAN, 2017).

The climate of the region is tropical, classified as C2wA'a". The average annual temperature of the municipality is between 25.5 and 26.0 °C. Average annual rainfall is between 1,400 and 1,500 mm.

The region is characterized by a lower rate of rainfall during the winter, a period that comprises the months of May to August.

The property's soil is classified as Red Yellow Latosol. These are soils dispersed throughout the state and are associated with reliefs, flat, gently undulating or undulating and occur in well-drained environments, being very deep and uniform in color, texture and structure in depth (EMBRAPA, 2006).

DATA COLLECTION

In the study area, 13 plots of 25 x 30 m were installed, randomly distributed, in a sampling intensity of 8% of the area. Installed plots had rectangular shapes and a constant area of 750 m². The number of trees per plot was not uniform, with an average of 24 trees per plot, totaling 306 trees sampled. The first and last trees of the plots were marked with black spray to demarcate the plot in the field and the trees contained within the plots were numbered with red paint.

The circumference at chest height (CAP) was measured at 1.30 m from the ground, with the aid of a tape measure and the total height (Ht) with the application of *smartphone Smart Measure,* version 1.6.4. The application was tested by Neto et al. (2016), who compared the use of this, with trigonometric hypsometers used in the literature, to the actual height of the tree felled and measured with a tape measure, concluding that the application demonstrates accuracy for estimating the total height of trees on flat terrain, presenting an error average of 2.37%.

VOLUME CALCULATION

To calculate the volume of wood in the plantation, the volumetric model by Stoate (1945) was used, adjusted to: *Khaya senegalensis* in the same study area carried out by Gama (2017), who evaluated several models presented in the literature, defining Stoate's as the most appropriate to estimate the volume of the species.

Gama (2017) adjusted the volumetric model through statistical analysis, based on the coefficient of determination (R^2) of 0.93

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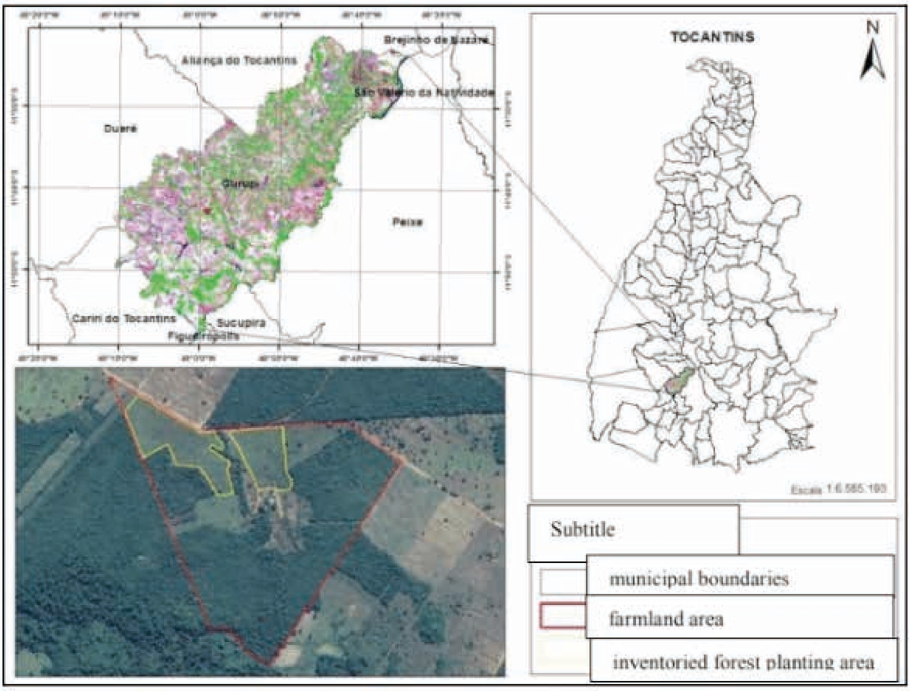

Figure 1: Location of the study area in the municipality and of the municipality in the State. Source: SEPLAN, (2017).

Number	**Models**
1	$Y = \beta 0 + \beta 1.Ht$
2	$Y= \beta 0 + \beta 1.DAP$
3	$Y = \beta 0 + \beta 1 (DAP^2.Ht)$
4	$Y = \beta 0 + \beta 1.DAP + \beta 2.Ht$
5	$Ln\ Y = \beta 0 + \beta 1.\ln DAP$
6	$Ln\ Y = \beta 0 + \beta 1.\ln DAP^2.Ht$
7	$Y = \beta 0 + \beta 1.DAP + \beta 2.DAP^2 + \beta 3 (DAP^2Ht)$
8	$Y = \beta 0 + \beta 1.DAP + \beta 2 (DAP^2Ht)$
9	$Ln\ Y =\beta 0 + \beta 1.\ln DAP + \beta 2.\ln Ht$
10	$Ln\ Y = \beta 0 + \beta 1.\ln DAP^3$
11	$Y = \beta 0 + \beta 1.DAP + \beta 2.DAP^2 + \beta 3.DAP^3 + \beta 4.DAP^4$
12	$Y = \beta 0 + \beta 1.DAP^3$
13	$Y= \beta 1.DAP^2 + \beta 2.DAP^2.DAP + \beta 3.DAP.Ht^2 + \beta 4.Ht^2$

Y total dry biomass, in kg; Ln = Neperian logarithm; β_n = regression coefficients; DAP = diameter at breast height; Ht = total height, in meters. Source: Melo et al., (2014).

Y = total dry biomass in kg; Ln = neperian logarithm; βn = regression coefficients; DAP = diameter at breast height; Ht = total height, in m. Source: Melo et al., (2014).

Table 1: Models adjusted for biomass estimation at the planting of Khaya senegalensis in the southern state of Tocantins.

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and the standard error of the Estimation (Syx%) of 1,45%.

$v = \beta_0 + \beta_1.H + \beta_2.D^2 + \beta_3.D^2.H$, where: V = volume; β_0 a β_3 = estimated coefficient; H = total height; D = diameter measured at 1.30 m from the ground.

Using the adjusted equation, the volume of each tree present in the plot, the volume of each plot, the average volume per plot and the volume in m^3 per hectare were calculated using Excel 2013 software.

QUANTIFICATION OF AERIAL BIOMASS

For the prediction of aerial biomass, destructive sampling was carried out, with the felling of 22 trees, these were weighed in the field with the aid of a scale, measured at total height and CAP (1.3 m) with a measuring tape and tape measure.

Trunk samples were collected in disks of approximately 2 cm, located at the base and in the middle of the tree. The methodology, adapted from Caldeira et al. (2015), to quantify biomass and organic carbon in stands of: *Araucaria angustifólia* (Bertol.) Kuntze, in which sampling consisted of removing discs from the stem at the base, mid-height and at the tip of the tree. The adaptation was made to use only the base and middle of the trunk, because the trees felled have a diameter of the upper part of the trunk very close to the diameter of the middle.

The discs identified in the field were taken to the laboratory for weighing while still wet. Weighing was carried out immediately after arrival at the Wood Processing laboratory at the Federal University of Tocantins.

The samples were previously dried naturally for 30 days and then placed in an oven for drying at a controlled temperature of 70°C (Ziemmer et al., 2016), until reaching constant weight, for subsequent determination of dry weight.

With the average wet and dry weights of the samples, the biomass of the felled trees was determined, through the expression (Soares et al., 2012):

$PS(c) = \frac{PU(c).PS(a)}{PU(a)}$ where: PS (c) = biomass, in kg; PU (c) = wet weight of the tree weighed in the field, in kg; PU (a) = wet weight of wooden disks with bark, in kg; PS (a) = dry weight of wooden disks with bark, in kg.

To evaluate the biomass in the African mahogany plantation, 13 linear models presented in the literature were adjusted, using Software R 3.4.1 (Table 1).

Table 1: Models adjusted for the Estimation of biomass in the planting of *Khaya senegalensis* in the south of the State of Tocantins.

To evaluate the model to be used, the adjusted determination coefficient indicators were considered (R^2), estimation standard error in percentage (S %) and graphical analysis of residuals.

CARBON STOCK

For estimating the amount of carbon in the aerial part of the plantation (trunk, branches and leaves), the biomass result was multiplied by 0.45.

Watzlawick et al. (2003), verified in several studies that there are variations in biomass and plantings with different edaphoclimatic conditions. But, the carbon contents, despite having some variations, were more stable, oscillating between 40 to 50%, with Average around 45% of the dry biomass.

Thus, for the Estimation of carbon, in this study, the Average: C=B.0.45 was used, where: C= carbon, in $kg.ha^{-1}$; B = Biomass, in $kg.ha^{-1}$; 0,45 = biomass to carbon conversion factor.

CONVERSION OF CARBON INTO CARBON DIOXIDE (CO_2)

The carbon dioxide captured by the aerial biomass of the plantation was estimated,

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converting the values of carbon (C) to carbon dioxide (CO2), multiplying the carbon stock by the conversion factor 3.67.

The conversion factor was obtained by the ratio between the molecular mass of carbon dioxide equal to 44 and the anatomical mass of carbon equal to 12 (Souza et al., 2012).

The amount of captured CO2 was estimated using the equation: CO2=C.3.67, where: CO2 = captured carbon dioxide, in $kg.ha^{-1}$; C = Carbono, in $kg.ha^{-1}$; 3,67 = carbon to carbon dioxide conversion factor.

RESULTS AND DISCUSSION

VOLUME QUANTIFICATION

In the forest inventory, 306 trees were evaluated in the 13 plots distributed in the study area. With the DBH (D) and height (H) data of these, the volumetric equation, adjusted from the Stoate model (1945), was used to determine volume:

Table 1: Models adjusted for biomass estimation at the planting of Khaya senegalensis in the southern state of Tocantins.

$v=2{,}327^{-3}+7{,}396^{-4}.Ht + 1{,}291^{-4}.DAP^2.Ht + \varepsilon$

Gama (2017) evaluated the accuracy statistics of Stoate's (1945) volumetric model, adjusted for the same study area, obtaining a determination coefficient of 0.930 and an Estimation standard error of 11.45%. The volume per hectare found for the area was 3.9375 $m^3.ha^{-1}$ (Table 2).

Table 2: Statistical results of the forest inventory, carried out in the African mahogany plantation.

It was observed that the average percentage error (E%): 9.49326, met the 10% precision level for forest planting, considering a definitive forest inventory, with 95% probability, which can be used for the Estimation of planting biomass (Table 2).

The inventory carried out in the study area recorded DBH and height characteristics, with values above the Average found in the literature (Table 3).

Warnasooriya et al. (2016), observed the growth performance of the species: *Khaya senegalensis*, with the age class between 1 and 3 years, in the Kurunegala division of Sri Lanka, region with Average annual precipitation of 1,400 mm, and resulted in Average height of 2.62 m and average DBH of 4.52 cm. Corroborating the assumption above that the planting of *Khaya senegalensis* studied has parameters above the Average cited in the literature, with Averages of 4.31 m in height and 6.68 cm DBH at 2 years and 8 months of age.

ESTIMATION OF BIOMASS, CARBON AND CARBON DIOXIDE

For the estimation of biomass, 13 models were adjusted using the independent variables diameter at breast height (DBH) and total height (Ht); of the 22 trees felled and weighed (Table 4).

It was observed that the statistical results of the 13 models varied among themselves, with the adjusted coefficient of determination (R^2aj) from 0.345 to 0.933 and the standard error of the Estimation (Syx%) with values between 5.945 and 18.592. Models 5 and 10 showed similar results (Table 4).

Models 7 and 11 presented the best results with R^2aj of 0.932 and 0.933 and Syx % of 5.952 and 5.945. Model 7 used height and DBH as input variables. Model 11 only uses DBH values as an independent variable, with statistical results greater than those of the tested models that include the height variable (Table 4).

Santana et al. (2008) consider an R2 of 0.85 high for a very comprehensive model, suggesting that an R^2aj greater than 0.90 is highly significant.

Model 1 had lower results than the other adjusted models, with results for R^2aj of 0.345 and Syx % of 18.592. The model used the

Statistics		Results
Average volume per hectare	$\bar{V}(m^3.ha^{-1})$	3,93751
Sample variance	$S^2 (m^3)^2$	0,00349
Standard deviation	$S (m^3)$	0,05917
Correction factor	f	0,91875
Standard error of Average	$S_{\bar{y}} (m^3.ha\text{-}1)$	0,20976
Sampling error	$E (m^3)$	0,37379
Error in percentage of Average	E (%)	9,49326
Coefficient of variation	CV (%)	±5,32730
Confidence interval	*IC* 0,95	3,56372 $m^3.ha^{-1}$; 4,3113 $m^3.ha^{-1}$

Table 2: Statistical results of the forest inventory, carried out at the African mahogany planting.

Parameter	Ht (m)	DAP (cm)
Maximum	11,1707	9,7403
Average	4,3156	6,6845
Minimum	2,8000	3,0558

Table 3: Height and maximum, average and minimum DBH of trees measured at planting.

Models	Coefficients					Syx	R^2aj
	β0	β1	β2	β3	β4	(%)	
1	1,888	2,935	-	-	-	18,592	0,345
2	-5,780	3,507	-	-	-	10,407	0,794
3	8,26199	0,03857	-	-	-	12,980	0,680
4	-8,724	3,018	1,193	-	-	9,102	0,843
5	-0,7384	1,8982	-	-	-	15,560	0,541
6	-1,0630	0,7218	-	-	-	14,162	0,619
7	-43,762411	15,543120	-0,943046	0,002355	-	5,952	0,932
8	-4,60822	3,18101	0,00418	-	-	10,640	0,785
9	-1,0619	1,4370	0,7285	-	-	14,548	0,598
10	-0,7384	0,6327	-	-	-	15,560	0,541
11	-204,38645	119,21757	-25,46024	2,52724	-0,09584	5,945	0,933
12	10,05906	0,02361	-	-	-	14,357	0,609
13	-5,93714	0,81960	-0,14551	0,05234	0,40933	9,396	0,832

Table 4: Statistical results of models adjusted for biomass. Table 4: Statistical results of the models adjusted for biomass.

independent variable height (Table 4). Melo et al. (2014), report low correlation of height with biomass and carbon.

Models 5 and 10 used the DAP logarithm (Table 4). It was observed that the logarithmic models presented lower adjustments than the arithmetic ones.

After statistical analysis of the models, a graphical analysis of the residuals for the adjusted models was performed, as a final criterion for selecting the most appropriate equation (Figure 2).

Observing the graphic distribution of the residuals (Figure 2), the accuracy of the Estimations is verified, by the amplitude of the residual values, in which model 11 had the best distribution among the 13 adjusted models.

The result observed in the graphic distribution of figure 2 was similar to the statistical evaluation previously presented in table 4, stating that model 11 is the most indicated to be used in this study.

Melo et al. (2014) estimated biomass and total carbon for caixeta trees, aged approximately 30 years, located in the municipality of Guaratuba, coastal region of Paraná. They adjusted 13 models, and graphically presented the residuals for total carbon, emphasizing that the residual analysis with low amplitude infers more accurate Estimations, providing a homogeneous variance.

Model 11 adjusted in this study for planting: *Khaya senegalensis* in the south of the state, it had higher rates than the other models, so it was used to estimate the biomass of the 22 trees felled, comparing the amount of biomass estimated through the equation with the observed biomass and the estimated and observed carbon (Figures 3 and 4).

The results presented for observed and estimated biomass and carbon, have approximate values, with a slight variation (Figures 3 and 4), the equation can be used for the rest of the plantation.

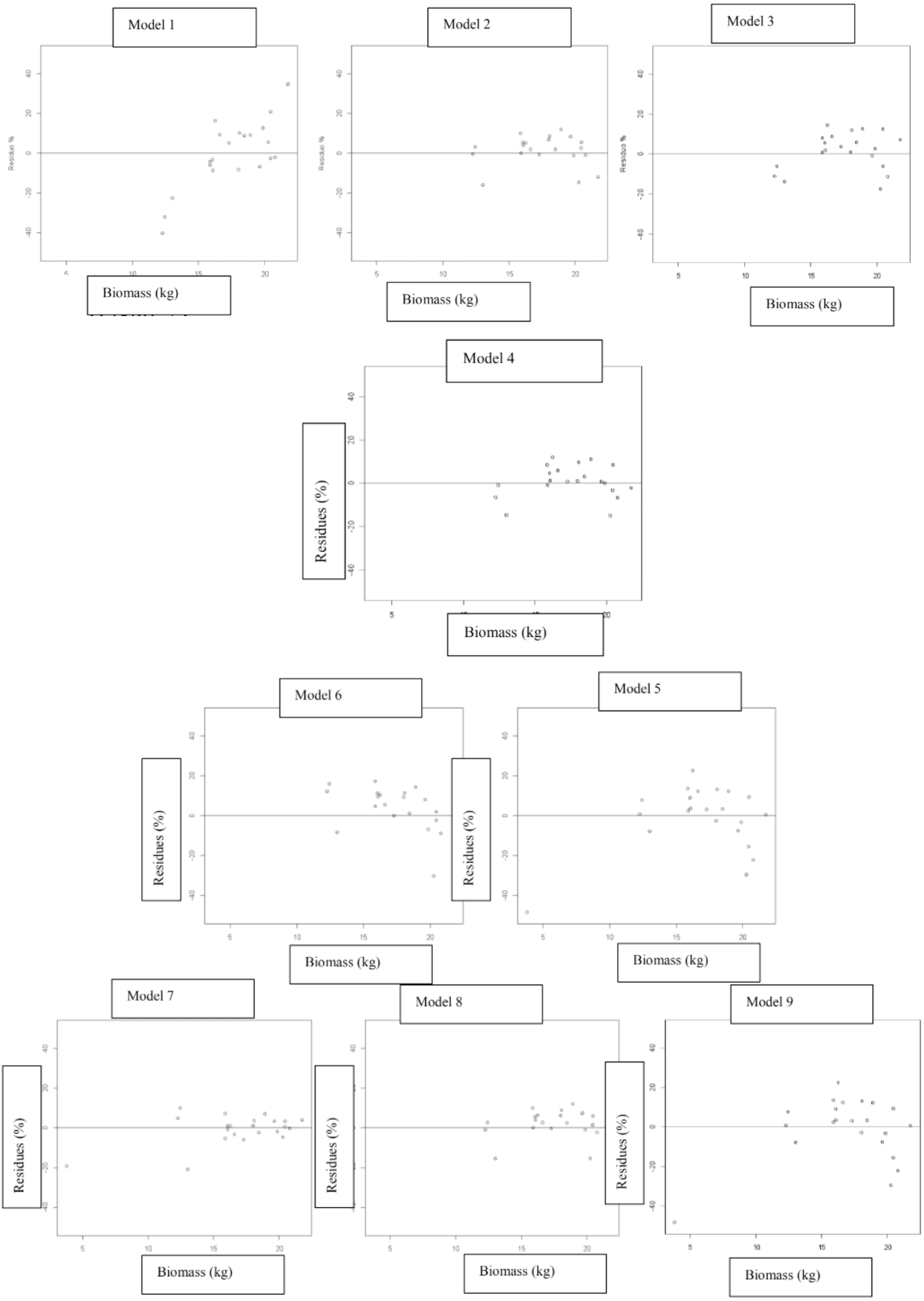
When relating the weight of trees felled to the amount of dry biomass (Figure 3), it is observed that approximately 60% of the weight of each tree is composed of dry biomass.

With the biomass results found through the equation, the carbon values were calculated, multiplying the biomass results by 0.45, and the captured carbon dioxide, multiplying the carbon result by 3.67 (Table 5).

Warnasooriya and Sivananthawerl (2016), estimated biomass and carbon in plantations of *Khaya senegalensis* distributed by Anuradhapura and Kurunegala, in the dry and intermediate zones of Sri Lanka, the plantations aged between 1 and 3 years, located in Kurunegala, a region that has edaphoclimatic characteristics closer to those found in Tocantins, had an average DBH of 2.14 cm, height of 2.62 m and estimated biomass of tree shoots of 4,44 $kg.árv^{-1}$. With a lower result than that presented in this study, which was 17,38 $kg.árv^{-1}$, for species with an average DBH of 6.68 cm and height of 4.31 m. The result can be explained by the fact that the plantations in Sri Lanka, cited above, are younger than the age surveyed in this study.

The average amount of carbon estimated per tree was 7.82 kg (Table 6), a value lower than that found by Silva et al. (2015), when they estimated carbon stock in the aboveground biomass in plantations of *Eucalyptus* spp. aged 2.3 years (27 months) in São Paulo, and found a total of 12,45 $kg.árv^{-1}$, average DBH of 8.35 cm. This situation can be explained by the fact that the eucalyptus plantation has a DBH higher than that found in this study, which was 6.68 cm. Another important factor to be raised is the fact that this is a region where the edaphoclimatic conditions are different from the area where mahogany is implanted.

Soares et al. (2005), adjusted equations to estimate carbon present in plantations


Model 1
Biomass (kg)
Model 2
Biomass (kg)
Model 3
Biomass (kg)
Model 4
Residues (%)
Biomass (kg)
Model 6
Residues (%)
Biomass (kg)
Model 5
Residues (%)
Biomass (kg)
Model 7
Residues (%)
Biomass (kg)
Model 8
Residues (%)
Biomass (kg)
Model 9
Residues (%)
Biomass (kg)

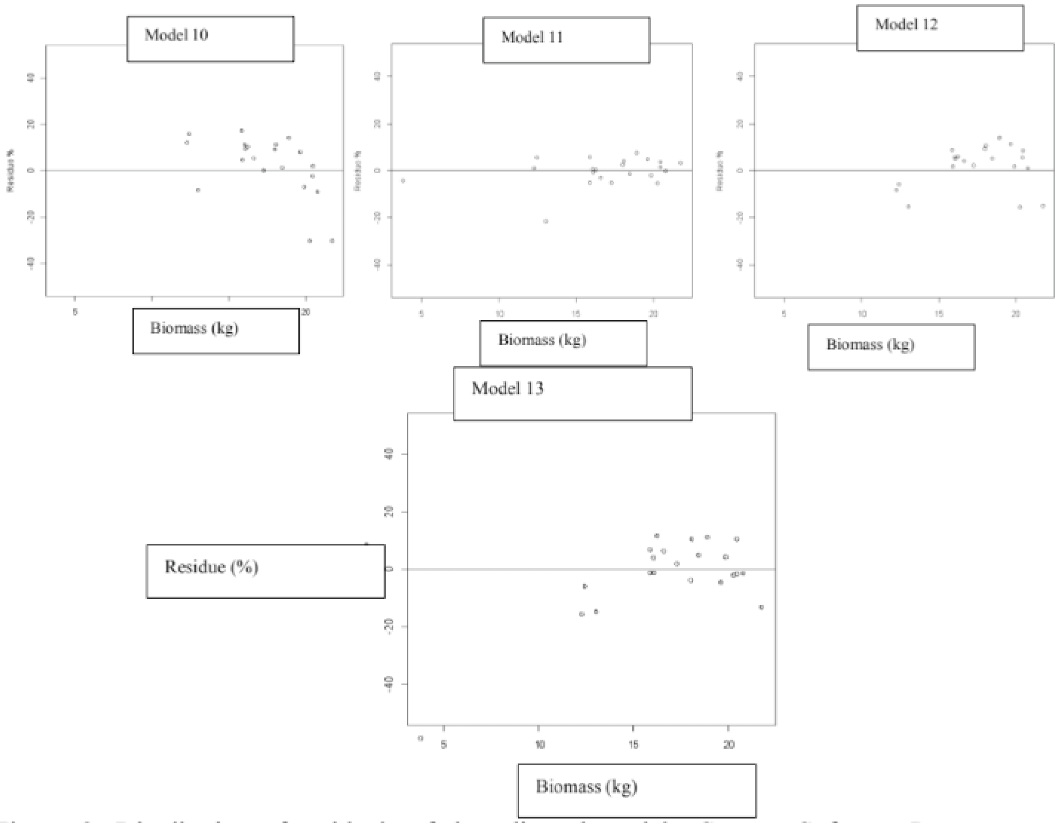


Figure 2: Distribution of residuals of the adjusted models. Source: Software R 3.4.1.

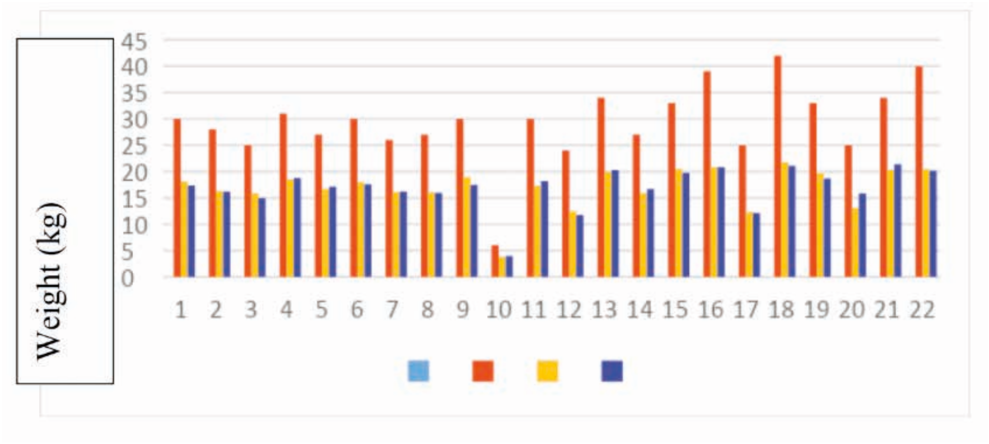


Figure 3: Weight of aerial part of felled trees, observed biomass and estimated biomass. Source: Author.

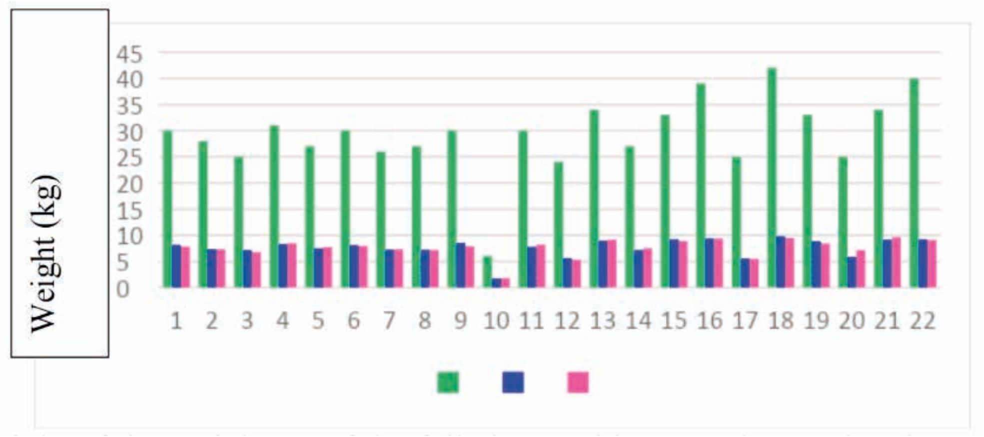


Figure 4: Weight of aerial part of felled trees, observed carbon and estimated carbon. Source: Author.

Estimation	Biomass		Carbon		Carbon dioxid	
	Average		Average		Average	
	per Tree (kg.árv^{-1})	Per hectare (ton.ha^{-1})	per tree (kg.árv^{-1})	Por hectare (ton.ha^{-1})	per tree (kg.árv^{-1})	Per hectare (ton.ha^{-1})
Results	**17,38**	**5,45**	**7,82**	**2,45**	**28,69**	**9,00**

Table 5: Estimations of biomass, carbon and carbon dioxide for planting: *Khaya senegalensis* in the south of Tocantins.

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of *Eucalyptus grandis* W. Hill, located in the eastern region of the State of Minas Gerais, at 32 months of age and mean DBH of 10.00 cm, found a carbon stock of 11,24 ton.$^{ha-1}$. A result superior to that presented in this study, remembering that there is the influence of the edaphoclimatic conditions found in the region and DBH higher than that of mahogany.

Observing the results of Table 6, it is noted that the accumulation of carbon dioxide by planting is close to twice the amount of accumulated biomass. Emphasizing the importance of planted forests in absorbing $CO_{2.}$

CONCLUSIONS

It was concluded that the adjustment of the allometric equation for estimating aerial biomass had satisfactory results, with R^2aj of 0.933 and Syx % of 5.945. The model with better results than the other adjusted ones used only the DAP as an independent input variable.

The biomass estimated through the planting equation had an average of 17,38 kg.árv^{-1}, with an approximate value to that observed in the slaughtered species, which was 16,92 kg.árv^{-1}. The estimated amount of biomass per hectare was 5,45 ton.ha^{-1}.

The carbon stored in the aerial biomass was 2,45 ton.ha^{-1} and the accumulated carbon dioxide from 9,00 ton.ha^{-1}. The amount of CO2 retained was equivalent to approximately twice the aerial biomass of the planting.

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