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Estimation And Valuation Of Individual Branches Biomass Of *Araucaria angustifolia* (Brazilian-Pine)

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Abstract:
Background*: Araucaria angustifolia is the main forest species in southern Brazil, and although the crown has significant biomass, research concerning the underused branches biomass estimation and valuation is scarce. Herein we quantified and modeled individual biomass of branches (B) and aciculated branches (AB) of Araucária, pellets production, and valuated the biomass.*
Materials and Methods*: Based on length and base circumference of 209 branches, we applied a stepwise regression transforming the independent variables, followed by Box-Cox transformation of dependent variable. The valuation of the branch biomass considered different uses, including pellets.*
Results*: We identified a mean of 58.7 branches per tree, with 4.06 m in length and 24.04 cm in base circumference. The mean AB biomass was 1.64 kg and B biomass 6.47 kg. Transformations of independent variables and Box-Cox transformation improved dry biomass estimations. The total mean biomass per hectare reached 16,330.93 kg.ha^{-1} for B, and 4,139.52 kg.ha^{-1} for AB. The use of thicker branches may result an income of R$ 7,568.81 with pellets commercialization.*
Conclusion:*Branches can reach large dimensions and high biomass accumulation. The Box-Cox transformation was efficient to improve dry biomass modeling, which can be used for management or biomass estimations, and dynamics studies. The branches biomass and pellets are suitable for income.*
Key Words*Biomass modeling; Araucária crown; Araucária Forest; renewable energy*

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I. Introduction

Known the canopy structure is crucial to understand the relationships among functionality, structure and environment in forest stands. Crown information is more important for uneven-aged forests, where different species have the ability to adapt their structures to capture scarce resources efficiently, or even not allow that its competitors have access to these resources, contributing to forest condition monitoring and tree development[1,2]. In this context, tree development can be sustained only by a faster expansion of the crown, leading to longer and thicker branches to support leaf mass increase[3].

In relation to the canopy dominance of native forests in Brazil, the Araucária Forest (Mixed Rain Forest) inserted in the Atlantic Forest biome is noteworthy. The canopy is often formed mainly by *Araucaria angustifolia*(Araucária) canopies that can occupy wide spaces, directly influencing the competition for resources among the arboreal individuals. Araucaria occupies mainly the plateaus of the forests in the states of Southern Brazil, and fragments observed in the Southeastern region, occurring at altitudes from 200 m to more than 1500 m in various geological, pedological, geomorphological and climatic conditions[4].

Araucária is a heliophilous dioecious species of the family Araucariaceae, with long lifespan, that can reach up to three meters in diameter and 50 m in height. According to Brack and Grings[5], the young tree of *A. angustifolia* has a pyramidal form, acquiring the shape of a candelabrum in the adult phase with long branches arranged in 8 to 15 whorls. As stated by Wendling and Zanette[6], the Araucária is formed by three completely distinct morphogenetic elements: 1) orthotropic stem (vertical); 2) primary branches (horizontal branches, plagiotropic); and 3) secondary branches or foliar (aciculated branches). The crown morphology is influenced by natural pruning, occurring when a branch is shaded by the above crown and by the competing trees, reducing photosynthetic rate and light intensity, inducing branch death[3].

Analyzing biomass per unit area in *Araucaria angustifolia* stands, Caldeira et al.[7] observed for 32-year-old trees that stem corresponded to 53.5% of the total aerial dry biomass, 18.9% for bark, 18.5% for living branches, 7.1% for aciculated branches and 2% for dead branches. In this way, only living branches including aciculated branches, correspond to 25.6% of the total tree biomass. On natural trees, Roik et al.[8] identified that branches are the third component contributing to the total aboveground biomass of *A. angustifolia*, however as the DBH increases, the branches biomass becomes the second tree compartment contributing to the total aboveground biomass. Thus, considering the importance of biomass to maintaining the forest ecosystem and the carbon stock[8,9], more studies are necessary focusing on other tree compartments than the stem, such as individual branches, comprising ecological aspects over the economic aspects[10].

Studies characterizing the Araucária crown are still scarce and not focusing on branches, such as Costa and Finger[11], relating tree competition and the dimension of the trees, and Klein et al.[12], addressing the crown morphometry. Regarding biomass, examples are the research by Schumacher et al.[13] and Caldeira et al.[7] analyzing compartmentalized biomass of planted Araucárias.

Individual branches biomass information can also be valid to explore possible uses of this tree compartment, usually wasted, such as handicrafts, energy use[14], or sawn wood, since according to Mattos[15] the Araucária branches have high resistance due to the tissue layers conformation.

The present research is based on the hypothesis that branches of adult Araucária trees can reach size and biomass compatible with small trees. Therefore, the objective of this research was to quantify the individual biomass of branches and aciculated branches of adult Araucárias in a native fragment of the Araucária Forest. For this, biomass estimation was modeled based on length and base circumference of the branches, contributing to more precise biomass estimations of this compartment with promising uses.

II. Material And Methods

Study area characterization

The study area is located in the municipality of FernandesPinheiro, in the Southeasthern region of Paraná State (Southern Brazil) under the coordinates 25°31'3.96"S and 50°33'1.50"O with an altitude of 830 m, totaling an area of 20 ha of Mixed Rain Forest with predominance of Araucária, in a small private rural property. The climate of the region is classified as Cfb (Köppen), Subtropical Moist Mesothermic (tempered, with cool summers and winters with occurrence of severe frosts, and no dry season). The average annual temperature is 19 °C, the average monthly minimum temperature is 13.9 °C and the average maximum monthly temperature is 26.1 °C. The annual precipitation ranges between 1.400 and 1.600 mm and the average relative humidity of the air is 74%[16]. The study area has a total of 14 ha, in which was realized a census of trees with diameter at breast height greater than 10 cm. The density of Araucária trees between 40 cm and 70 cm in diameter in the study area was of 43 trees.ha^{-1}.

Data collection

The data used in this research are from 30 harvested *Araucaria angustifolia* trees with diameter at breast height (DBH) ranging from 40 to 70 cm. The evaluated trees are from a sustainable forest management experiment carried out on the "Imbituvão" project[17,18], in three forest management units of 1 ha. After harvest, length and base circumference with bark of 209 no damaged branches were measured for all branches that remained attached to the trees. The inclusion limit of the branches was of eight centimeters in circumference with bark, considering the parts with a diameter less than 8 cm as aciculated branches. The selected branches were detached from trees, separating the branches and aciculated branches compartments for weight evaluations. After that, were removed two samples of 5 cm in length of each branch, one corresponding to the basal portion and the other to the portion at 50% of the branch length, along with samples of aciculated branches for drying in laboratory. The samples were fresh weighted and subsequently dried in a drying oven at 60 °C until the weight remained constant for determination of moisture content. After tree fall, the number of branches and whorls of each tree was counted.

Biomass estimation and Statistical analysis

For biomass estimation and statistical analysis, initially a Pearson Correlation matrix was performed at a 95% confidence interval, among the dependent variables (X) (branch and aciculated branches dry biomass) and the independent variables (length and base circumference of the branches). Stepwise regression was applied for branch and aciculated branches biomass estimations, applying the several transformations (Supplementary Information - SI1) to the independent variables corresponding to the Step I (Figure 1) to verify the most correlated form of the variables with biomass.

After adjusting the models, the dependent variable (Y) was transformed by the Box-Cox method for the estimations based on length and base circumference (Step II) (Figure 1), resulting in eight equations, which can be written as follows[42]:

$$y^{(\lambda)} = \begin{cases} y^{(\lambda)} \ (\lambda \neq 0) \\ Log\, y \ (\lambda = 0) \end{cases}$$

Where: $y^{(\lambda)}$: transformed value of the variable; y: Original value of variable; λ: Constant obtained by the maximum of the log-likelihood function.

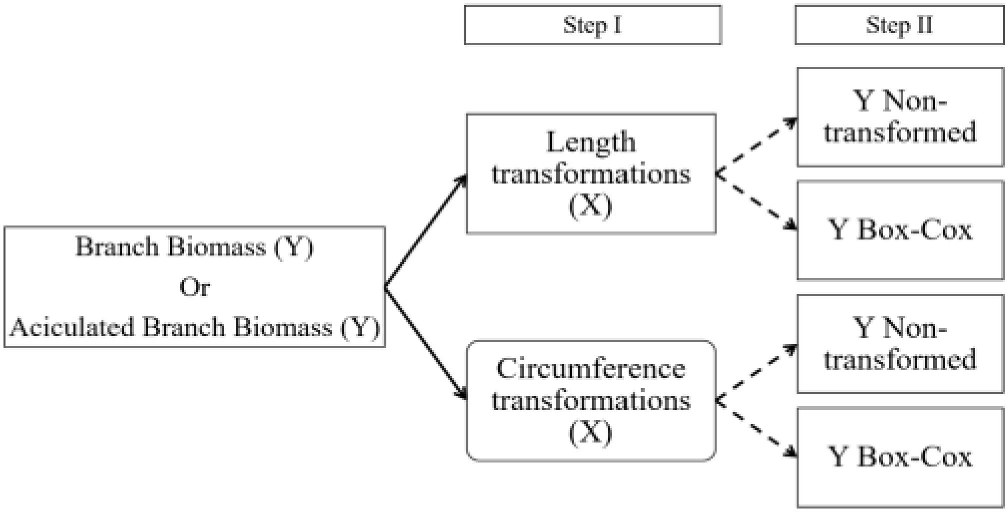


Figure 1: Flow diagram of branch and aciculated branches biomass analysis methodology

The variables transformations aimed to verify possible improvements in the homogeneity of variance and normality of residuals. For the evaluation of these items, was applied the Kolmogorov-Smirnov Test (K-S) and the Scale-location graphical method, which correlates the information of the standardized residues with the estimated values. The models were evaluated by the Adjusted Coefficient of Determination (R^2_{adj}), Standard Error of Estimations in percentage (S%) and graphical distribution of residues based on the recalculated values for the dependent variable of interest.

Pellet production and biomass valuation

To test the viability of using Araucária branches in the production of pellets, 40 kg of branches biomass was processed in a chopper mill to fractionate the biomass.The fractionated biomass was sieved through 12 and 10 mesh (1.70 mm and 1.4 mm, respectively). Then the sieved biomass was used to produce pellets in a laboratory pellet press AmandusKahl model 14-175 with flat die and production capacity of 30 $kg.h^{-1}$.The matrix has a passage of 6 mm in diameter, with a cutting blade adjusted to cut the pellets with 25.5 mm in length and rollers rotation speed of 1200 rpm.The pellet production temperature ranged from 70 to 90°C.

The evaluations of the produced pellets were: a) determination of the hygroscopic equilibrium humidity in a climatic chamber at a temperature of 20ºC and 65% relative humidity (ISO 18134-2-17);b) length, diameter and unit density of the pellets, based on sampling 30 pellets (ISO 17829-15);c) bulk density (Equation 1) in Becker of known volume filled with the pellets at equilibrium moisture content (ISO 17828-15);d) mechanical durability test of three 500 g samples in a rotating container at a speed of 50 rpm for 10 min (ISO 17831-1-15), then the fine content of 125 g samples was determined with opening sieves of 3.35 mm (ISO 18846-16);e) quality class for residential and/or commercial, and industrial use (ISO 17225-2, 2014).

$$Bd = \frac{m\ (g)}{V\ (cm^3)} \qquad \text{Equation (1)}$$

Where: Bd = bulk density($g.cm^{-3}$);m= mass(g);V= volume(cm^3).

The total biomass of branches was estimated based on the mean dry mass of the branches, mean number of branches per tree, and mean number of trees per hectare. For the valuation of the Araucária branches for firewood, wood chips, and pellets we considered the mean dry mass of 13.5% of the branches at the base of the tree crown. We applied the market value based on the data of the State Secretariat for Agriculture and Provision[19] for firewood R$ 135.00 per cubic meter and wood chips R$ 142.00 per ton (density of 386 $kg.m^{-3}$). For pellets the price of R$ 900.00 per ton was consulted on Pinus pellet producers in the region (density of 600 $kg.m^{-3}$).

III. Result

Regarding branches number analyzed per tree, it ranged from two to 13 whole branches per tree, totaling 209 branches measured, and a mean of 58.7 branches per tree. The average length of the branches was 4.06 m and the circumference with bark at the base was of 24.04 cm. The longest branch had 9.20 m and a base circumference of 33.21 cm (10.57 cm in diameter), whereas the smallest branch in circumference (8.20 cm), also had the shortest length 0.55 m. The greater branch base diameter was of 42.0 cm (Table 1). The mean number of whorls per tree was of 8.47.

Table 1: Descriptive statistics on the length, circumference and diameter of the base of the evaluated *Araucaria angustifolia*branches.

Statistics	Length (m)	Base Circumference with bark (cm)	Diameter (cm)	Number of Branches (n.tree^{-1})
Average	4.06	24.04	7.65	58.7
Maximum	9.20	42.00	13.37	94
Minimum	0.55	8.20	2.61	36
S	2.02	7.54	2.40	14.92
CV (%)	49.87	31.36	31.36	25.43

Where: S: Standard deviation; CV: Coefficient of variation; CI: Confidence interval for the mean with 95% of significance.

Regarding biomass, branches dry biomass ranged from 0.06 to 28.67 kg, and a mean biomass of 6.47 kg, on the other hand aciculated branches mean dry biomass was of 1.64 kg, ranging from 0.06 to 5.43 kg. Due to the high amplitudes of the values found for the branches and aciculated branches, the coefficients of variation resulted in high values. The moisture content was similar for branches and aciculated branches of *A. angustifolia*(Table 2).

Table 2: Descriptive statistics of fresh biomass, dry biomass and moisture content of branches and aciculated branches of *Araucaria angustifolia*.

	Branches				Aciculated branches		
Statistics	Fb (kg)	Db (kg)	MC (%)		Fb (kg)	Db (kg)	MC (%)
Average	13.80	6.47	53.37		3.75	1.64	56.31
Maximum	58.89	28.67	57.82		10.45	5.43	66.67
Minimum	0.13	0.06	43.75		0.14	0.06	47.73
S	12.83	6.09	2.98		2.00	0.94	4.75
CV (%)	92.98	94.00	5.59		53.48	57.16	8.43

Where: Fb: Fresh biomass; Db: Dry biomass; MC: Moisture content; S: Standard deviation; CV: Coefficient of variation; CI: Confidence interval for the mean with 95% of significance.

To estimate individual dry biomass of aciculated branches the base circumference of the branch showed better correlation than the length, whilst for branches biomass estimations both variables were suitable according to the correlation results (Table 3).

Table 3: Pearson correlation matrix for the length, circumference and dry biomass of branches and aciculated branches of *Araucaria angustifolia*.

	Length	Circumference	Aciculated branches biomass	Branches biomass
Length	1			
Base Circumference	0.9194**	1		
Aciculated branches biomass	0.3909**	0.5864**	1	
Branches biomass	0.9166**	0.9179**	0.4979**	1

Where: **: significant at 99% of significance.

After the stepwise regression procedure, using several transformations of the independent variables, it was verified that the transformations improved the quality of the adjustments. However, for branch biomass estimation as a function of the length no improvement was observed, since the variable without transformation also composed the adjusted model, as shown in Table 4. Box-Cox transformation also improved the estimations when the dependent variable was the branch circumference in comparison to the branch length, based on the R^2 increase and error reduction (Table 4). For the estimation of dry branch biomass as a function of the circumference, the square root of the circumference was not significant when the dependent variable was transformed by the Box-Cox method.

Table 4: Adjusted models and statistics for estimates of dry biomass of branches and aciculated branches of *Araucaria angustifolia* as a function of the length and the circumference of the base of the branch.

Dependent Variable	Transfor-mation	Equations	R^2_{adj}	S(%)
Branch (Length)	NT	$DBbr = 6.5231 + 5.8033.Length - 12.1132.\sqrt{Length}$	0.862	34.88
	B-C	$DBbr^{0.0606} = 0.6033 - 0.0525.Length + 0.3560.\sqrt{Length}$	0.860	35.11
Branch (Circf.)	NT	$DBbr = 39.6047 - 31.7568.\ln(Circf^2) + 34.1738.\sqrt{Circf}$	0.917	27.03
	B-C	$DBbr^{0.1010} = -0.1274 + 0.2039.\ln(Circf^2)$	0.925	25.74
Aciculated branches (Length)	NT	$DBlt = 0.6831 + 0.3824.\ln(Length^2)$	0.212	50.73
	B-C	$DBlt^{0.3434} = 0.8510 + 0.1154.\ln(Length^2)$	0.168	52.13
Aciculated branches (Circf.)	NT	$DBlt = -1.7713 + 0.7057.\sqrt{Circf}$	0.348	46.17
	B-C	$DBlt^{0.3838} = 0.0940 + 0.2208.\sqrt{Circf}$	0.325	46.97

Circf: Circumference at the base of the branch, in centimeters; NT: Dependent variable Non-transformed; B-C: Dependent variable transformed by Box-Cox; R^2_{adj}: Adjusted Coefficient of Determination; S(%): Standard error of estimate, in percentage.

According to the graphical analysis of the residues for the adjusted models, the four models evaluated were similar, indicating a greater error for the smaller circumferences when the dependent variable was not transformed, reaching an accuracy expressed by the R^2_{adj} greater than 92% and an error of 25.74%. On the other hand, aciculated branches dry biomass estimations were considered unsuitable based on the low adjusted coefficient of determination and standard error of estimate of about 50%, also showing discrepancies for the branches of smaller circumferences. In general, the Box-Cox transformation did not lead to significant improvements in the adjustments, taking into account the R^2_{adj} and S_{yx} (%).

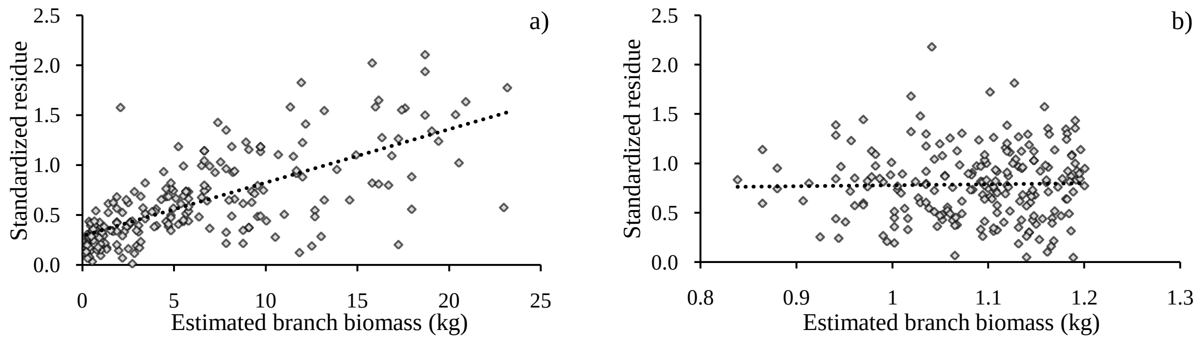
The results shown in Table 5 indicated that the dependent variable transformation by the Box-Cox method resulted in an improvement in the normality of the residual distribution, according to the Kolmogorov-Smirnov Normality Test.

Table 5: Results for the normality test of Kolmogorov-Smirnov residues.

	Equation	Dn	p-value
Branch (Length)	Y Non-transformed	0.1653	0.0000**
	Y Box-Cox	0.0705	0.0134*
Branch (Circf)	Y Non-transformed	0.1284	0.0000**
	Y Box-Cox	0.0496	0.2403ns
Aciculated branches (Length)	Y Non-transformed	0.1210	0.0000**
	Y Box-Cox	0.0327	0.8475ns
Aciculated branches (Circf)	Y Non-transformed	0.0881	0.0005**
	Y Box-Cox	0.0330	0.8366ns

Where: **: significant at 99% of significance; *: significant at 95% of significance.; ns: Non-significant; Dn: Calculated value for K-S test; p-value: significance of the result.

In relation to the homogeneity of the variances of branch dry biomass estimations, when the length and branch base circumference were applied in the models, the homoscedasticity was only obtained with the Box-Cox transformation, as shown in Figure 2. For the estimates with the untransformed values, there was heteroscedasticity, that is, tendency of increase in the variance as the size of the branch increases.



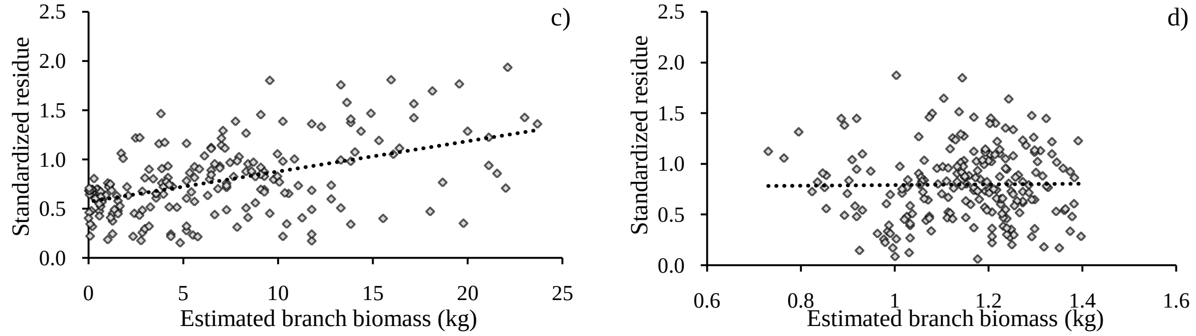


Figure 2: Scale-location graphs: A) Branch biomass as a function of length; B) Branch biomass transformed by Box-Cox as a function of length; C) Branch biomass as a function of circumference; D) Branch biomass transformed by Box-Cox as a function of circumference. Standardized residue: $\sqrt{residue}$

For the aciculated branches biomass estimations, the Box-Cox transformation of the dependent variable was not efficient to solve the problem of heteroscedasticity, however, the transformation minimized the trend of increase of the variance, as shown in Figure 3.

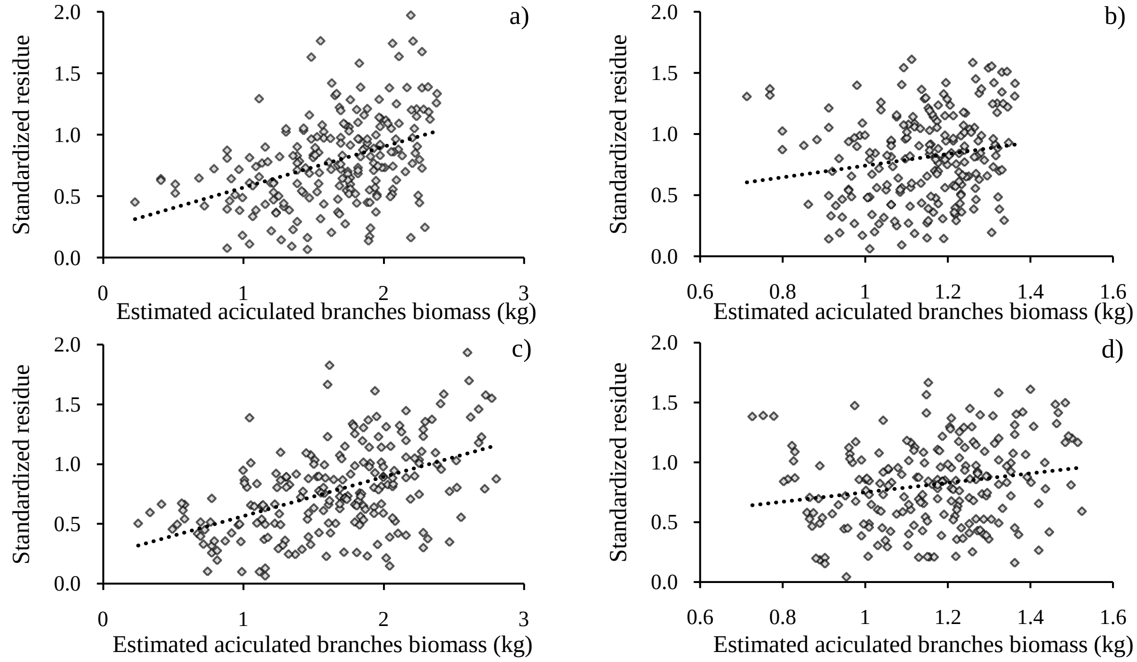


Figure 3: Scale-location graphs: A) Biomass of aciculated branches as a function of length; B) Biomass of aciculated branches transformed by Box-Cox as a function of length; C) Biomass of aciculated branches as a function of circumference; D) Biomass of aciculated branches transformed by Box-Cox as a function of circumference. Standardized residue: $\sqrt{residue}$

The properties of *Araucaria angustifolia*branches pellets are shown in the Table 6 below, while the pellets produced are shown in Figure 4.

Table 6: Properties of *Araucaria angustifolia*branches pellets

Properties of *Araucaria angustifolia*branches pellets							
Humidity content (%)	Length (mm)	Diameter (mm)	Unit denity ($kg.m^{-3}$)	Bulk density ($kg.m^{-3}$)	Fines content (%)	Mechanical Durability (%)	Calorific Value ($MJ.kg^{-1}$)
5.76	26.5	6.0	1.235	686.0	0.19	96.8	19.13

According to the ISO 17225-2, 2014 quality classification, the pellets of Araucária branches were suitable for residential and industrial uses, when the humidity, length, diameter, density and fines content properties were considered. Mechanical durability, however, was not within the limits of the class A1 and A2. The same was observed for industrial use, in which the pellets were suitable for industrial use in the I3 quality.

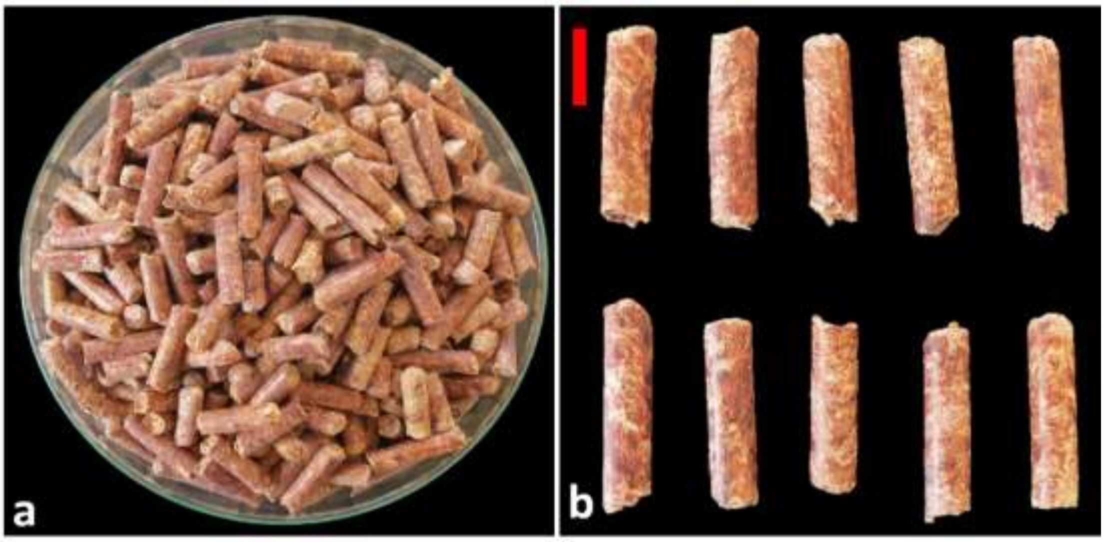


Figure 4: Pellets of *Araucaria angustifolia*branches. a) bulk density of *Araucaria angustifolia* branches pellets. b) detail of the produced pellets (Scale bar: 10 mm)

The total mean biomass per hectare for the forest fragment analyzed reached 16,330.93 kg.ha^{-1} for branches, and 4,139.52 kg.ha^{-1} for aciculated branches (Table 7). For the 13.5% of the branches of the crown, corresponding to the branches greater than 10 cm in diameter, the mean dry biomass was 14.13 kg per branch, and a mean of 11 branches greater than 10 cm in diameter per tree. However, only 22 of the 30 trees evaluated had branches greater than 10 cm in diameter, thus we considered only 70% of the trees per hectare to estimate biomass for the total area. The biomass of the branches greater than 10 cm totaled 155.43 kg per tree, and more than 5 tons (Table 8). Finally, considering the viability of pellets production, the possible income for the use of branches biomass (not considering the aciculated branches biomass), in the comparison to the income generated by firewood, and wood chips, the commercialization of pellets can generate a significant income for the land owner, reaching the income of R$ 7,011.00 per hectare (Table 9).

Table 7: Total dry biomass (kg.ha^{-1}) of *Araucaria angustifolia* branches and aciculated branches, considering an average of 58.7 branches per tree and a density of 43 trees greater than 40 cm in diameter per hectare.

Statistics	Branches				Aciculated branches		
	Db (kg)	**Total per tree (kg)[a]**	**Total for the area (kg.ha^{-1})[b]**		**Db (kg)**	**Total per tree (kg)[a]**	**Total for the area (kg.ha^{-1})[b]**
Average	6.47	379.79	16,330.93		1.64	96.27	4,139.52
Maximum	28.67	1,682.93	72,365.95		5.43	318.74	13,705.86
Minimum	0.06	3.52	151.45		0.06	3.52	151.45
S	6.09	357.48	15,371.77		0.94	55.18	2,372.65
CV (%)	94.00	94.00	94.00		57.16	57.16	57.16

Where: Db: Dry biomass; [a] Dry biomass multiplied by the average number of branches per tree (58.7 branches per tree); [b] Dry biomass per tree multiplied by the average number Araucária trees in the area (43 trees per hectare).

Table 8: Dry biomass (kg.ha^{-1}) of *Araucaria angustifolia* branches greater than 10 cm in diameter, considering an average of 11 branches per tree and a density of 30 trees greater than 40 (70% of total density in the area) cm in diameter per hectare.

Statistics	Branches		
	Db Ø >10 cm (kg)	**Total per tree (kg)[a]**	**Total for the area (kg.ha^{-1})[b]**
Average	15.26	167.86	5,035.8
Maximum	28.31	311.41	9,342.3
Minimum	11.48	126.28	3,788.4
S	3.84	42.24	1,267.2
CV (%)	25.16	25.16	25.16

Where: Db: Dry biomass of branches greater than 10 cm in diameter; [a] Dry biomass multiplied by the average number of branches with diameter greater than 10 cm in diameter per tree (11 branches per tree); [b] Dry biomass per tree multiplied by the average number Araucária trees in the area (30 trees per hectare).

Table 9: Income (R$.ha^{-1}) for different uses of *Araucaria angustifolia* branches biomass: firewood, wood chips, and pellets.

Uses for Branches Biomass	Branches biomass (kg.ha^{-1})	Conversion factor (kg to m^3)	Total biomass (m^3.ha^{-1})	Price in the market (R$.m^{-3})	Total Income (R$.ha^{-1})
Firewood[a]	5,035.8	0.00179	9.01	135.00	1,216.90
Wood Chips[b]	5,035.8	0.00147	7.40	142.00	1,051.17
Pellets[c]	5,035.8	0.00167	8.41	900.00	7,568.81

[a]560 kg.m^{-3}; [b] 680 kg.m^{-3}; [c] 600 kg.m^{-3}.

IV. Discussion

The results indicated that Araucária branches can provide a significant amount of biomass. In this context, the mean dry biomass of a single branch observed herein is comparable to the biomass of entire trees, equivalent to *Ateleiaglazioviana*Baill, with DBH ranging from 2.0 to 16.6 cm and height of 3.3 to 11.9 m[20]. Similarly, other trees occurring in the biome have mean biomass similar to the observed for Araucária branches, such as *Aloysiavirgata* Pers. and *Machaeriumstipitatum* Vogel[21]. Thus, it suggests that the crown can be managed as a source of biomass, promoting the sustainable management of the species, necessary to counter the fragmentation and pressure over the forest remnants[22]. Moreover, the branches play ecological roles, contributing to the litter content, since 15.64% of litter in a Mixed Rain Forest was from Araucária branches and 4.34% from aciculated branches, corresponding to approximately 1.3 Mg.ha^{-1} [23]. Besides that, nutritional cycling occurs due to the natural pruning of the branches and aciculated branches which contains significant nutrient contents[24,25]. Therefore, there is a need to better understand biomass components of *A. angustifolia* on native remnants[8] and management must include ecological, genetic, social and economic aspects[26].

The biomass estimations considered for the trees are for the entire crown, being justified its use only for felled trees or plantations. However, for native trees the crown biomass management must consider only part of the crown as a source of woody material. In this context, considering that the thick branches of *A. angustifolia*represents 20% of the total photosynthetic biomass, of which 13.5% are branches greater than 10 cm in basal circumference[27], we adopted the 13.5% of the basal branches to estimate the income from the management of basal branches.

The branches with greater biomass and dimensions were observed at the base of the crown, in comparison to the smaller branches of the tree apex (smaller dimensions), being formed by younger and less dense tissues. For this reason, branches harvesting management aiming for income from forest remnants can be performed easily without comprising tree apex and apical dominance, and may even benefit tree growth[28]. Besides that, crown management can be encouraged since branches biomass reduce as the tree age increase for *A. araucana*[29], and greater branches biomass is not clearly related to an increase in age and tree volume[8].

According to Brack and Grings[5], adult trees of *A. angustifolia* have branches arranged in eight to 15 whorls, having six to 10 branches per whorl, which means around 90 branches per tree. The results for number of branches and whorls observed herein are similar to the reported by Brack and Grings[5]. Applying the mean dry biomass multiplied by the average number of branches found in the present research a single tree corresponds to of 379.79 kg for branches and 96.27 kg of aciculated branches per tree. Moreover, in the evaluated samples was observed a total of 43 trees.ha^{-1} with DBH greater than 40 cm. In this way, considering the *A. angustifolia* density in the area and the mean biomass for the evaluated components, the total branches and aciculated branches biomass reached 20.4 Mg.

Since branches and leaves biomass represent about 16.8% and 4.6%, respectively, of the above ground biomass of Araucária[24], the crown of large trees should be treated with special attention in biomass research. The relevance of crown biomass in other biome, the Deciduous Seasonal Forest, where the biomass of the three largest trees corresponded to about 60% of the total aerial biomass[30]. Moreover, the authors highlighted that the compartment that contributed most to the aerial biomass were the thick branches, equivalent to 32.8% of the total aerial biomass in the areas surveyed. Considering the Mixed Rain Forest fragments in an advanced stage, usually the larger trees are centenarian Araucárias, and detailed surveys of the Araucária canopy compartment are still scarce due to the difficulty to access and evaluate this information, or by law that restricts the management of the trees. Added to this, the significant biomass and volume of the Araucária crown must be considered in interventions in the forest[31,32].

Another relevant parameter associated with the Araucária branches that must be considered is the carbon stock[8]. According to Dallagnolet al.[33], the carbon content for the dry mass of the branches and aciculated branches of Araucária are 44.46% and 45.27%, respectively. Applying these rates to the mean values of dry biomass (379.79 kg for branches and 96.27 kg of aciculated branches), there are for a single adult tree about 168.85 and 43.58 kg of fixed carbon, respectively, in the compartments branches and aciculated branches, totaling about 9.1 Mg in the sampled area. Hence, only these two components of the tree can comprise a significant carbon stock, contributing to reducing climate change issues, which have been widely discussed at the global level.

The contribution of biomass and carbon stock retained in the Araucária branches in the remnant evaluated in this study, can be considered expressive in comparison to other remnants of Araucária forest. In a remnant with a density of 12.2 trees.ha^{-1} with DBH greater than 40 cm Ebling and Péllico Netto[34] identified a carbon stock of 3.76 Mg.ha^{-1}. In the same region of our study, in the Irati National Forest, Orellana et al.[35] recorded 42 individuals per hectare of *A. angustifolia*, of which 24 individuals.ha^{-1} were above 40 cm DBH. Using the same methodology previously applied, in this forest fragment, there are about 7.39 Mg.ha^{-1} of carbon stored in the compartments branches and aciculated branches. Finally, it is important to highlight that the number of branches and whorls may change depending on the carbon balance and light environment, since it is observed for the related species *A. araucana*[36].

Although significant, the carbon stock observed in the forest evaluated herein is lower than the observed in other studies, this may be explained by the samples considering the trees greater than 40 cm in BHD. Schikowskiet al.[37] simulated above-ground carbon stocks of the tree community of a Mixed Rain Forest, determining a total stock of 88.44 Mg.ha^{-1}. Thus, using the quantities quoted in the researches of Ebling and Péllico Netto[34] and Orellana et al.[35] for Araucária, only the branches of trees greater than 40 cm BHD would represent 4.25 and 8.36%, respectively, of the total carbon stored in areas of Mixed Rain Forest.

The management of branches biomass and carbon stock may also be important in *A. angustifolia* stands. Hentz et al.[38] carried out a census in 508 60-year-old trees, of which 105 were individuals with DBH greater than 40 cm. Using the average values generated in the present research, each individual can represent about 550.21 kg of dry branch biomass and a total of 57.77 Mg. For this reason, branches biomass of commercial plantations could have a destination for a more specific use with a sustainability nature, for example for energy generation. This is more relevant, since the branches are considered residues, which are left in the forest or underused and marketed for reduced monetary amounts for firewood use. It should also be noted that large branches form large knots in the stem, which could also be used in a more appropriate way instead of being treated as a residue of the crown, because it is a material of high ornamental and calorific value[39].

The main advantage of branches and aciculated branches as an energy resource is their low moisture content (18%) when collected after the natural pruning. However, the disadvantages are the high ash content and the low basic density[40]. In this study, however, the moisture content of about 55%, similar to the reported by Roik et al.[8], can be considered high in comparison to the reported in the literature for naturally pruned branches, thus the managed material may require drying before application.

Branche circumference proved to be suitable and provided accurate results for individual dry biomass estimations of branches and aciculated branches as well, whereas branch length was suitable for branches biomass estimations. Based on this, biomass estimations based on circumference is adequate when is possible to direct measure this variable in the crown of felled trees, whereas length of the branch is more appropriate for living trees, since it is possible to measure branch length considering the crown projection in the soil. However, estimations of aciculated branches biomass presented low accuracy, that can be a consequence of the data collection, due to the damage of branches in the tree fall interfering on the data collection methodology. In addition, Wendling and Zanette[6] reported that the longevity of the *A. angustifolia*aciculated branches is about five to seven years, that suggest a constant renewal that are also subject to climatic events, such as strong storms and winds that can detach this material from the branches.

Regarding coefficient of determination and standard error, the equations without dependent variable transformation were very similar to the equations in which the Box-Cox transformation was performed. Nevertheless, for the complementary analyzes of the residues, the Box-Cox transformation improved the results, correcting the residues distribution in biomass estimations of branches in the smaller circumference classes, once they are not outliers, but very young branches with reduced woody material and biomass. Although the crown structure can be considered different and we considered individual branches estamations, the results for *A. angustifolia* were similar to those observed by Kutchartt et al.[29], that estimating total foliage and branches biomass for *A. araucana* reached errors ranging from 24.1 to 28.7% and coefficient of determination greater than 0.96. It is worth mentioning, that the models applied by the aforementioned authors considered DBH, total height and crown characteristics as independent variables, whereas herein estimations were based only on branches data.

The Box-Cox method also proved to be suitable in the study of Avila et al.[41], to model the frequency distribution of three species, one of them *A. angustifolia*, under different environmental conditions and historical disturbances. The transformation was efficient to meet the assumptions of residues normality and homoscedasticity, items required for the modeling application as considered in this study. On the other hand, Azevedoet al.[42] applying Box-Cox transformation to evaluate the improvement in the normality and homoscedasticity of the residues of a crop biomass experiment, concluded that the transformation was not always suitable. This situation was similar to that found in the present research, especially in the case of homoscedasticity of the residues of aciculated branches dry biomass, in which it was not possible to reach homogeneity of the variances.

Since Araucária is still under pressure the sustainable management must be considered, besides that the legislation that could be insufficient and incoherent[22], limits the management of the trees. Thus, the management and use of branches, managing its growth and use per year, can provide significant amount of income[4] for small landowners that have limited or no income from the forest remnants. Moreover, since the number of branches increases according to the tree age, the conservation of the species can be achieved by promoting the conservation-by-use[43], and payment for environmental services by the carbon retained in the crown.

There are other uses proposed for branches biomass, such as composites[44] and chipboards[45] (Rios et al., 2015). In this context, the use of branches biomass for energy proposed herein may increase income for landowners, mainly pellets that are associated to several advantages such humidity reduction, increase of density facilitating and reducing transport costs together with an increase in energy efficiency[46], resulting in higher added value. Pellets of Araucária branches proved to be suitable considering its calorific value, that is superior to Pinus pellets[47], and according to the standard classifications. Nevertheless, it is suggested to improve the quality for residential uses, which can include the use of branch biomass without bark.

V. Conclusion

In conclusion, Araucária branches can reach large dimensions, and high biomass and carbon accumulation, that can be estimated based on branch base circumference and length, which is improved when the dependent variable was transformed. Finally, biomass research regarding the branches and aciculated branches dynamics, currently with few uses and wasted, can contribute to the acquisition of more detailed information in this field, contributing for more sustainable economic uses along with incorporation in projects that involve payments for environmental services, i.e. carbon fixation, in areas with predominance of Araucária trees.

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