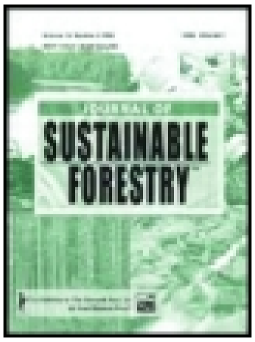

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Effect of species and log diameter on the volumetric yield of lumber in northern Brazilian Amazonia: preliminary results

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ABSTRACT

Volumetric yield analysis is critical to optimizing performance in the timber industry. In the Amazon and in the Amapá state, this information is still little known and scarce, and therefore this study was developed to obtain and analyze the volumetric yield coefficient of ten commercial tree species and to test the variation by diameter class. We collect data of volumetric yield from for ten commercial species. For each species, the yields in different diameter classes were analyzed, as well as the yield difference between the species. The overall yield obtained for the sawmills (43.95%) and the yield of each species are within the established standards for operations in the industry according to the legal requirements. There were no differences ($p \geq 0.05$) in diameter classes for species with the exception of *Dinizia excelsa* and *Handroanthus albus*. However, there was no linear increase ($p \geq 0.05$) between the diameter and yield of lumber for all species. The species *Dinizia excelsa, Hymenolobium petraeum, Ocotea rubra* and *Vochysia guianensis* show a significant difference in yield for the other species due to the higher obtained values, however, they are statistically similar when compared to each other.

KEYWORDS

Lumber production; Amazon; forest management; sawmill; forest utilisation

Introduction

The Brazilian Amazon is home to almost one third of the world's humid tropical forests, with an estimated 60 billion cubic meters of logs (Hummel, Alves, Pereira, Veríssimo, & Santos, 2010), with the potential economic value being more profitable or equivalent to agricultural activities and mining Brazilian (Santana, Santos, Santana, & Yared, 2012; Veríssimo et al., 2006; Ribeiro & Rocha, 2009). In addition, it has been one of the leading tropical timber producing regions in the world, right after Malaysia and Indonesia (OIMT, 2012).

In its efforts to promote the optimal use of timber products from native forests, the Brazilian government has been developing and applying a set of resolutions and normative

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instructions through its inspections agencies to define the legal standards for the harvest and use of timber, aiming at maximum efficiency and waste reduction.

Among the set of laws regulating timber production, there is the CONAMA Resolution 474/2016 which establishes the use of sawn wood, which must be at least 35% of the volumetric yield coefficient and can be obtained individually by species or by the set of more processed species in timber industries. Thus, any sawmill that does not meet the established standard can face a penalty for excessive waste of raw material. Therefore, the search for increases in yield coefficient and in log transformation to final products such as sawn wood will positively influence areduction in the forest area required for producing the same volume of sawn wood (Gerwing, Vidal, Veríssimo, & Uhl, 2001; Veríssimo, Lentine, & Lima, 2002).

Although there are approximately more than 80 timber species being processed at sawmills in the Amazon, a company will often specialize in less than 30 species (Veríssimo, Souza Junior, Stone, & Uhl, 1998). Of all the commercial species extracted from the authorized management plans, a good percentage are of the species *Dinizia excelsa* (Angelim vermelho), *Manilkara huberi* Ducke (Massaranduba) and *Dipteryx odorata* Aubl. Willd. (Cumarú), which consist in greater export and economic return (Danielli, Gimenez, Oliveira, Santos, & Higuchi, 2016; Gerwing et al., 2001; Veríssimo et al., 1999).

In this way, it is important to gather information regarding the yield of sawn wood, as well as to compare the levels of production in the different sizes of the logs and between among the most commercialized tropical species in the processing industry in the Amazon region. Furthermore, quantifying the by-products of this process is a necessary action for the best use of the species, in addition to being able to subsidize future decisions on the industrial performance of the company with a reduction of expenses and losses in the production process (Biasi & Rocha, 2007; Melo, Rocha, Rodolfo Junior, & Stangerlin, 2016; Piovesan, Souza, & Souza, 2013).

Among the sawn wood producers in the Brazilian Amazon, Amapá State is only the sixth (Hummel et al., 2010), but it is currently in the process of forest concession, promoting its State Forest – FLOTA/AP as a primary production forest (IEF, 2017). In this context, it is expected that log production and consequently sawn wood will increase on a large scale. Accordingly, accurate and reliable analyses of the yield of sawn wood from commercial species are needed to guide maximum utilization and to define efficient regulations that support the production of legal timber.

Until now, few studies on the commercial yield of sawn wood in Amapá have been developed or published, and accurate information and analyses are essential for the legal functioning of the industry in the inspection agencies. The present study intends to fill this gap in order to: 1) measure the yield of lumber obtained from different species and diameter classes, and 2) develop yield coefficients for the species. we test the hypotheses that the studied species present a volumetric yield coefficient above 35%, which is proposed by Brazilian law and that it increases as a function of the size of the logs processed in the sawmill.

Materials and methods

Description of the study area and species selection

The sawmill occupies an area of approximately seven hectares, with space reserved for a log storage yard, mechanical sector for maintenance of heavy machinery, as well as the main production shed and one for the inventory of sawed products; the administrative sector makes up the rest of the industry with spaces reserved for housing and staff canteens.

The main industrial shed has two production lines and each one is composed of the following equipment: 1- Complete lamination (IKL®); 1 – winch of the log carrier car (Schiffer®); 1 – winch for pulling and turning logs 10 HP; 1 – Log carrier (four heads) (IKL®); 1 – Tape Saw (4 heads) (IKL®); 1 – Alignment machine with feed mechanism/ winch (Schiffer brand); 1 – Multilayer with 30 HP engine (Águia®); 1- Multilayer with 50 HP engine (Águia®); 2- Cutter machine (power of 7.5 CV) (IKL®); 1- Jointer (4 axles, power of engines 01 of 10 HP, 3 of 7.5 HP, 1 of 5 HP, 01 of 3 HP of elevation of bench) (DAMBROZ®); 1 – Extractor (Power 7.5 HP)1–300 kva generator set (STEMAC®).

This study included a yield evaluation of sawn wood from ten commercial species which, besides being established by the consumer market as the most worked, are those that presented processing of more than 50 logs during the analyzed period. These species also come from harvest in the annual operating plans and present good economic returns for the company, namely: *Dinizia excelsa* Ducke (Angelim vermelho), *Dipteryx odorata* (Cumarú), *Manilkara huberi* L.(Massaranduba), *Carapa guianensis* Aubl. (Andiroba), *Hymenolobium petraeum* Ducke (Angelim pedra), *Goupia glabra* Aubl. (Cupiúba), *Handroanthus albus* Vahl. Nichols. (Ipê), *Hymenaea courbaril* L. (Jatobá), *Ocotea rubra* Mez (Louro vermelho) and *Vochysia guianensis* Aubl. (Quaruba tinga).

Sampling and data collection

Timber in logs

All timber arriving in the sawmill yard is of forest management plan origin, where harvesting is permitted for commercial species with a minimum diameter of 50 cm. After cutting the tree, the trunk with full length is sectioned into logs of different lengths to facilitate transportation logistics to the sawmill.

For each species, 50 logs with an average diameter over 50 cm were randomly selected. The diameters of the base and top with bark were measured for each log, in addition to the total length and volume being estimated by means of strict cubing. Hollow measurements were also made, measuring the diameters that the dimensions occupied in the log. One measurement was performed for logs that had no distortions in length. The logs of all species were measured by obtaining the diameter along the trunk in four sections according to the logging methodology proposed by Smalian (Expression 2). Thus, four measures of diameter were obtained from each log and a mean diameter of the log was computed to compose the distribution in size classes and to verify the yield in each size class of diameter.

Sampling adequacy was carried out to estimate the optimum number of logs that would be representative to compose the yield study. An acceptable error limit of 10% was adopted for all cases with a probability of 5%. Thus, we considered the data for an infinite population according to expression 1:

$$n = \frac{t_\alpha^2 S^2}{E^2 + \frac{t_\alpha^2 S^2}{N}} \qquad (1)$$

Where: n = optimal number of logs; t^2 = tabulated value of the Student's t-test (α = 0.05); S^2 = sample variance; E^2 = permissible error limit (10%); N = total number of logs measured (50).

Log volume was estimated according to CONAMA Resolution No. 411 of May 6, 2009. The volume was calculated individually by the geometric method using the Smalian formula (Expression 2):

$$V_i = \frac{\pi}{4} \times \left(\frac{g_i + g_{i+1}}{2}\right) \times L \qquad (2)$$

Where: V_i = section volume i; g_i = cross-sectional area of section base in m^2; g_{i+1} = cross-sectional area of section top in m^2; L = length of the section in m.

The diameter measurement occurred in two central sections on the log and at the extremities. This task followed the standard established by Conama Resolution 476/2016. For measuring the hollow, with a tape measure were measured the different dimensions at the base of the log following the cardinal directions to compute the size of the hollow diameter. The mean diameter of the hollow was obtained by the arithmetic mean of these directions and the length of the internal space of the log with hollow was obtained with a ruler in a scale of centimeters. The calculation of the volume of the hollow followed the same pattern of the volume of the log without hollow.

Sawn wood

The wood cutting operation is carried out according to following process. In the main cutting, the logs were first admitted into the process by passing through a vertical band saw with a flywheel diameter of 1.25 m and a cutting height of 80 cm. The first cuts were made by removing the bark and the first piece (usually a board), thus forming a semi-block. The semi-block was subsequently cut successive times, producing wood pieces with different dimensions. A circular gang saw edge machine with a cutting height of 80 mm was used for adjusting and defining the widths of the wood produced by sawing the semi-block, with which wood pieces with dimensions ranging from 30 to 110 mm and lengths ranging from 2 m to 7 m were produced. The last process was carried out in the cutter machine, where defects such as knots, cracks, and holes from insect attacks, etc. were removed. After alignment and narrowing, the wood pieceswere sent to the warehouse.

Estimated sawn wood volume and volumetric yield

For calculating the sawn wood volume, all the pieces obtained from cutting each log were quantified and had their thicknesses, widths, and lengths measured. The thickness measurements at each extremity were obtained by a tree caliper. The width measurements at each extremity of the wood and the length were measured using a tape measure. Thus, 'T' (thickness) and 'W' (width) and length (L) of each sawed product from the logs were obtained.

After determining the product volumes, they were added together, there by obtaining the volume of sawn wood for each processed log. The determination of the wood utilization or volumetric yield of the species was carried out by the ratio between the sawn wood volume and the volume of the processed logs with the bark, as given by the expression 3:

$$R\% = \frac{\sum_{i=1}^{j} V_p}{\sum_{i=1}^{j} V_t} \times 100 \quad (3)$$

Where: *R%* = Sawn wood yield for each log (i) of the species (j) (%); *Vp* = Volumes of all products per log (i) of the species (j) (m^3); *Vt* = Volumes of all logs (i) of the species (j) (m^3).

The volumetric yield for each species was obtained from the arithmetic mean of the yield values (%) obtained from each log. The general average yield of the sawmill was obtained from the arithmetic mean of the yield values obtained by the ten analyzed species.

In general, the volumetric yield coefficient is calculated individually in wood green for each log after the sawing process. After the sawing process, the quantity of primary and secondary products is inspected and taken to the stockroom. In the storage room or greenhouse, it will occur in loss of moisture and consequently will result in swelling and volumetric retraction of the product. In this step, volumetric yield data will not be computed because it is derived from processed wood still with moisture.

Statistical analysis

A first attempt was made to analyse the yield data in relation to normality and homogeneity. The main descriptive measures were calculated and the Shapiro-Wilk test ($\alpha = 0.01$) was applied to the data for all analyzed species. Thus, two experimental designs were adopted, and both were completely randomized. The first considered a comparison of the average yield between species; and the second considered the average yield of each species in different diameter class. The replicates were the 50 logs measured.

In the second design, each treatment (diameter class) had a number of different replicates. When the species were considered as a treatment, the replicates were the same. In both cases, variance analysis was performed to verify if treatments (species and diameter class) caused a significant effect on yield (%) at 95% probability. When a significant effect of treatments was identified, the Tukey test was used to discriminate the differences between their averages at 95% probability. All analyses were performed with Software R® version 3.4.1 (R Development Core Team, 2017), using package agricolae (Mendiburu, 2017).

Results

The overall yield found for the sawmill was 43.95% (Table 1). According to calculation of the optimum number of samples, the number of logs that would be needed ranged from 26 for *Vochysia guianensis* to 45 for *Goupia glabra*. In general, these results are in agreement with the standard error values found, suggesting that the sampling of 50 logs for each species is representative for developing this work. Only two species presented

Table 1. Quantification of products and volumetric yield obtained in the cutting process of 50 logs of the 10 analyzed commercial species in a medium-sized sawmill in Porto Grande, Amapá, Brazil.

	Average±S.E (p > .05)		Quantity		Total volume (m^3)			
Species	Diameter (cm)	Length (m)	Logs	Sawn prod.	Logs	Sawed	Yield (%)	S.E
Carapa guianensis	55.17 ± 2.76	9.83 ± 0.67	N = 50; n = 33	2643	119.37	44.22	37.8	4.35
Hymenolobium petraeum	62.14 ± 2.59	5.93 ± 0.66	N = 50; n = 39	5000	81.54	44.72	54.41	2.44
Dinizia excelsa	103.05 ± 6.02	5.11 ± 0.48	N = 50; n = 37	4551	182.79	100.31	54.4	2.81
Dipteryx odorata	62.23 ± 2.58	5.52 ± 0.66	N = 50; n = 37	3903	84.04	33.28	39.07	3.05
Goupia glabra	54.17 ± 2.73	8.05 ± 0.67	N = 50; n = 45	1994	86.57	34.27	39.72	0.92
Handroanthus albus	54.14 ± 2.71	7.09 ± 0.67	N = 50; n = 38	3143	81.87	31.7	39.7	2.73
Hymenaea courbaril	67.35 ± 4.24	8.05 ± 0.68	N = 50; n = 39	5943	145.72	58.06	39.85	2.35
Ocotea rubra	59.69 ± 2.58	9.85 ± 0.68	N = 50; n = 41	2655	137.39	61.57	44.72	1.76
Manilkara huberi	58.69 ± 2.79	8.87 ± 0.66	N = 50; n = 40	4948	121.95	48.79	40.3	2.16
Vochysia guianensis	64.84 ± 2.66	8.02 ± 0.67	N = 50; n = 26	6020	131.59	63.01	49.57	8.0
Total average	64.15 ± 4.70	7.6 ± 0.69		4080	117.3	51.99	43.95	3.05

Note: N = Number of logs measured for each species; n = Number of logs that would be sufficient for each species (p<.05, df = 49); S.E = standard error of the mean for estimating the confidence interval at 95% probability.

hollow logs such as *Goupia glabra* with 15 hollow logs and *Dinizia excelsa* with 30 hollow logs. These hollow logs make up only 9% of the overall sample.

The highest values of wood yield considering the logs without the hollow were obtained for the species *Hymenolobium petraeum* and *Dinizia excelsa*, with 54.41% and 54.40%, respectively. However, these similar results differ in the diameter and volume of the log found, because although *Hymenolobium petraeum* logs present smaller dimensions (Diameter average = 62.14 cm; Log vol. = 81.54), the utilization capacity in sawn wood (sawed products = 5000) is superior to *Dinizia excelsa*, with the largest dimensions found in the sawmill (Diameter average = 103.05 cm; Log vol. = 182.79 m^3). The species that have the highest quantities of sawed products were *Vochysia guianensis* and *Hymenaea courbaril*.

The volumetric yield of *Vochysia guianensis* was the third largest (49.57%) found, being higher than the general average of the sawmill, thereby indicating good performance even though the average diameter of the log is lower than *Dinizia excelsa*. Although the *Hymenaea courbaril* species presented the second largest quantity of sawed products, its volumetric yield (39.85%) was below the general average. The results obtained for the yield of *Hymenaea courbaril* are different when compared to *Ocotea rubra* because this species has a smaller average diameter and smaller quantity of sawed products, but with a better use of the wood (44.72%) and being slightly above the average found for the sawmill.

The lowest volumetric yields were presented by the species *Carapa guianensis* (37.8%), *Dipteryx odorata* (39.07%), *Handroanthus albus* (39.70%) and *Goupia glabra* (39.72%), indicating that more than 60% of the sawn wood of these species does not consist in the main sawmill products. These results indicate that although the logs of these species showed a great variation in the measurements of trunk diameter and length, as shown by the confidence interval (Table 1), a significant number of logs processed with tortuosity defects, cracks and conicity may have influenced significantly in the low volumetric yield.

The yield values obtained are within what is established by legal requirements, where the use of sawn wood is over 35%. Thus, the sawmill studied is within the standard for which the law prescribes in inspection procedures of industries that consume or transform products and wood by-products of native origin.

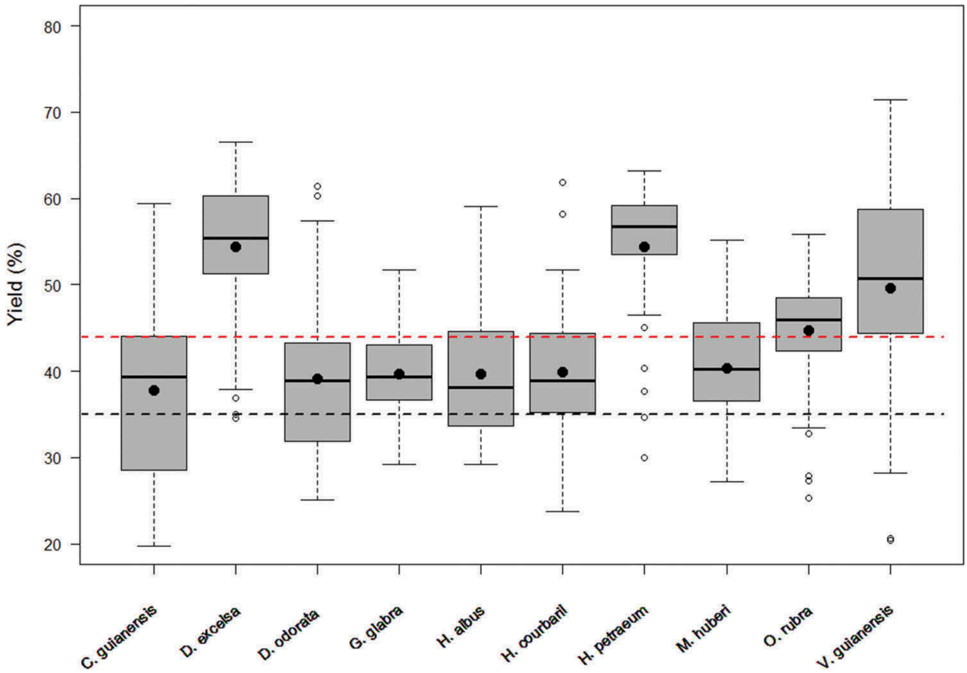

Figure 1. Boxplot for the sawn wood yield from the 10 commercial species of a sawmill located in Porto Grande, Amapá.

Note: The horizontal line in black inside each box indicates the median; the black dots are the averages; the horizontal line in red indicates the general volumetric yield (43.95%) obtained for the sawmill considering the 10 species together; the dashed line in black indicates the acceptable yield (35%) by CONAMA resolution 474/2016.

In the yield distribution for each species (Figure 1), it is estimated that at least 75% of the logs for *Hymenolobium petraeum, Dinizia excelsa, Ocotea rubra*, and *Vochysia guianensis* present above-average volumetric yield for the sawmill. However, the species *Carapa guianensis, Dipteryx odorata, Goupia glabra, Handroanthus albus, Hymenaea courbaril* and *Manilkara huberi* suggest that between 50% and 75% of the logs present a lower volumetric yield than the sawmill (43.95%), meaning that they tend to have low use of sawn wood for main products (such as floors, frames, etc.), and that more than 55% tend to be for secondary products such as slats, rafters, boards and other similar products.

The average and median values found suggest that yield data tend to a normal distribution. This fact corroborates the results of the Shapiro Wilk test ($p > .01$) for the species *Handroanthus albus*: (p-value > 0.01); *Goupia glabra* (p-value > 0.01); *Hymenaea courbaril* (p-value > 0.01); *Manilkara huberi* (p-value > 0.01) and *Vochysia guianensis* (p-value > 0.01). The species *Carapa guianensis, Hymenolobium petraeum*, and *Dinizia excelsa* present a slight deviation from normality, indicating an asymmetric negative distribution where the values of the average yield of these species are smaller than the median.

In the comparison between yield data between species, the F-test value presented a statistical difference (p-value < 0.001; F = 27.67; df = 490), meaning there is

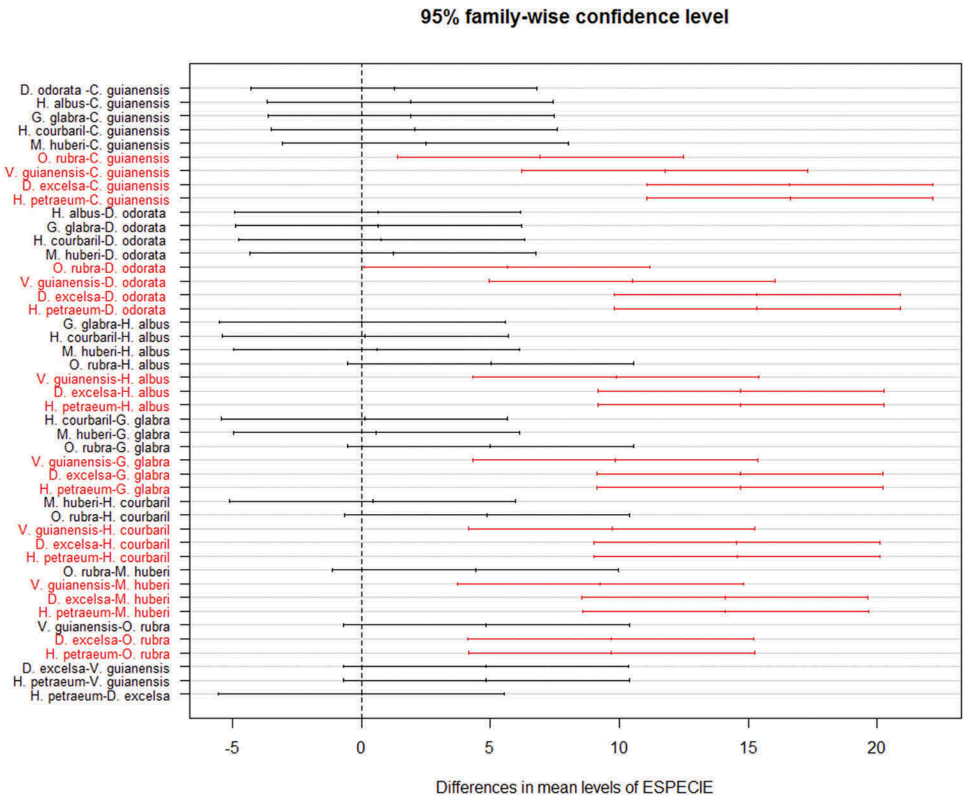

Figure 2. Contrasts of yield averages among the ten analyzed species.

Note: Species in red indicate that the contrast between the yield averages differs from zero according to the Tukey test at 95% probability.

Table 2. Comparison of mean yield differences among the ten species analyzed. Means followed by the same letters did not differ significantly by the Tukey test ($p < .05$).

Species	Average yield (%)
Hymenolobium petraeum	54.41a
Dinizia excelsa	54.40a
Vochysia guianensis	49.57ab
Ocotea rubra	44.72bc
Manilkara huberi	40.30cd
Hymenaea courbaril	39.85cd
Goupia glabra	39.72cd
Handroanthus albus	39.70cd
Dipteryx odorata	39.07d
Carapa guianensis	37.80d

a probabilistic relationship of yield differentiation between species, which was expected. The results of the Tukey test (Figure 2, Table 2) show differences in the comparisons of yield averages for *Carapa guianensis* and *Dipteryx odorata* with at least four species. The coefficient of variation found for this experiment was 19.83%, indicating good experimental accuracy.

The average yield of *Carapa guianensis* is statistically different from *Ocotea rubra, Vochysia guianensis, Dinizia excelsa* and *Hymenolobium petraeum*. The species *Dipteryx odorata, Handroanthus albus, Goupia glabra*, as well as *Hymenaea courbaril* and *Manilkara huberi* indicate there are similarities between the yield averages from a statistical point of view. Theoretically, much of the statistical significance obtained in comparing the average contrasts of the ten species is due to *Hymenolobium petraeum, Dinizia excelsa* and *Vochysia guianensis*. These species presented differences from the others and were similar when compared to each other. It is also noticed that these species of larger yield present differences in averages with the species *Handroanthus albus, Goupia glabra, Hymenaea courbaril* and *Manilkara huberi. Ocotea rubra* indicated that the contrast of averages does not differ from zero when compared to *Vochysia guianensis*, but is different from *Hymenolobium petraeum* and *Dinizia excelsa*.

This result was already expected since *Hymenolobium petraeum, Dinizia excelsa* and *Vochysia guianensis* concentrate the highest yield values. Despite the similarities in averages between these species, it is possible to observe the tendency to decrease or stability of the yield as a function of the analyzed diametric classes. This evidence showed that the increase in the logs' diameter did not provide a significant increase in yield, suggesting that the log volume in these species does not present a significant linear relation, although the yield average is higher than the sawmill's.

The similar averages between *Carapa guianensis, Handroanthus albus, Goupia glabra, Hymenaea courbaril* and *Manilkara huberi* suggest that the different log diameter dimensions, the volume of logs and the quantities of sawed products do not significantly interfere in the yield averages. Thus, it can be recommended that there is no need to select logs by diametric classes for these species (except for *Dinizia excelsa* and *Handroanthus albus*, according to the result shown in Figure 3), and that the establishment of different cutting methodologies can be tested to achieve high yields, or at least to approximate the average yield of the sawmill.

According to the result of the F-test, it was observed that there was no statistical difference (at a 95% probability level) between the yield values in the diameter classes, except for *Dinizia excelsa* and *Handroanthus albus* species (Figure 3). The variations in log diameter for these two species influence the yield of sawn wood; however, it has been observed that logs with a larger average diameter tend to have lower yield values.

Unlike *Dinizia excelsa* and *Handroanthus albus*, the yield per diameter class for the other species suggests a statistical similarity, although as the diameter of the log increases, the yield values tend to maintain equality, evidencing low variation. However, even though there is no statistical difference between diametric classes, the small percentage differences in yield between classes is very important within a scale of production, not only for reducing operating costs, but also in reducing the waste generated by the sawmill, Sawmills are generally underutilized in the study region. Therefore, the variation trends observed between classes can generate large differences in a large-scale sawing scenario.

In Figure 3 it can also be observed that only the first diameter class of *Hymenolobium petraeum* and *Dinizia excelsa* presented superior yield to the other species in all diametric classes. For *Carapa guianensis, Goupia glabra, Handroanthus albus* and *Hymenaea courbaril*, logs with an average diameter of 50 and 60 cm tend to have an average yield of less

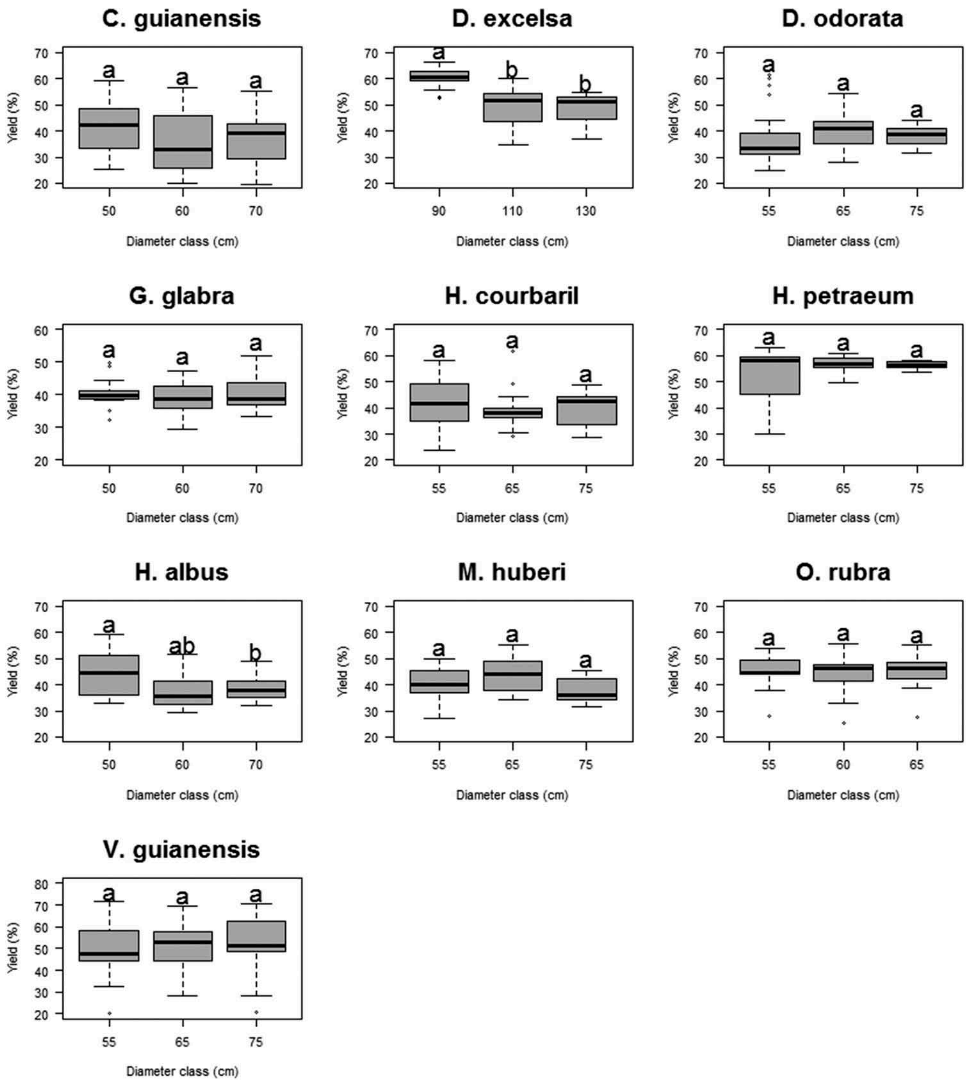

Figure 3. Boxplot for the yield data by diameter class for the 10 commercial species analyzed in a sawmill located in Porto Grande, Amapá.

Note: Averages followed by the same letter do not differ statistically from each other by the Tukey test at 95% probability. The coefficients of variation for the design of each species suggest good experimental precision, being: *Carapa guianensis* = 27.42%; *Hymenolobium petraeum* = 13.89%; *Dinizia excelsa* = 11.20%; *Dipteryx odorata* = 22.53%; *Goupia glabra* = 12.06%; *Handroanthus albus* = 19.72%; *Hymenaea courbaril* = 19.34%; *Ocotea rubra* = 14.99%; *Manilkara huberi* = 17.81%; *Vochysia guianensis* = 28.93%.

than 40%. In general, in terms of yieldit can be said that *Hymenolobium petraeum* was the species that presented the best results and *Carapa guianensis* presented the worst, even with no statistical difference between the diameter classes.

Discussion

Studies on sawn wood production and analysis of the volumetric yield of commercial species are significantly important for the development of the timber sector and sustainable wood production in the Brazilian Amazon (Danielli et al., 2016; Gerwing et al., 2001; Iwakiri, 1990; Silva et al., 2015; Ribeiro & Rocha, 2009).

Among the states of the Legal Amazon, the State of Amapá comprises just over 2% of all industries processing tropical timber, ahead of only Acre (1.07%) and Roraima (1.66%). Despite the gradual growth in recent years, the sawn wood yield in Amapá does not exceed 45%, which is similar to that found in the present study. For example, considering 2009 production, consumption of wood in logs was over 940,000 cubic meters with bark with a generation of 410,000 cubic meters of sawn wood (Hummel et al., 2010; Pereira & Veríssimo, 2010).

Several factors affect the volumetric yield in the sawmills that process Amazonian commercial species, with the main factors being storage in the storage yard, type of equipment used in the cutting process and type of generated products. Regarding the storage type, log volume loss may occur mainly due to insect damage (Gerwing et al., 2001).

The classes with the largest average diameter where the yield is lower occur as a result of larger diameter logs, presenting an incidence of internal defects such as hollowing, cracks, insect attack, etc., which directly lead to a reduced yield of sawn wood. Another factor that must be taken into account is the conicity of the logs that influence the variety of obtained products, which may mean that some diametric classes are not adequate to obtain products with homogeneous dimensions.

The low yield can also be caused by cracks that occur during extraction and are responsible for the large volume of wood lost during storage in the company's yard, with *Manilkara huberi* (Massaranduba) being more susceptible(Danielli et al., 2016; Gerwing et al., 2001; Melo et al., 2016; Williston, 1981). Regarding the equipment used, a large source of waste at the sawmills could be from producing wood with excessive thickness, which compensates the variation in the thickness in the sawing and reduces the incidence of processed wood below the normal size (Gerwing et al., 2001; Hebert, Grondin, & Plaice, 2000; Steele, 1984). In this case, primary products significantly contribute to reducing the yield, being compensated later by the volumetry of secondary products or greater use of small parts from re-sawing (Gerwing et al., 2001).

The overall yield of below 50% found in this study may be related to species-specific factors such as conicity and tortuosity, log diameter, cutting techniques, and equipment used (Murara Junior, Rocha, & Trugilho, 2013). The conicity and tortuosity also have a significant influence on the use of wood, as significant diameters of the thick and thin tip generate an excessive loss of material since the obtaining of sawn wood will occur from a tip with smaller diameter. Tortuosity can generate a greater amount of waste, reducing yield (Afrifah & Frimpong-Mensah, 2014; Hebert et al., 2000).

In this study, the log split type followed the pattern of most sawmills in the Amazon region, being tangential. This type of log splitting consists of the tangential cut to the growth rings of the tree which, in addition to providing primary products with better performance, increases the yield and presents smaller product width limitation and faster drying (Manhiça, Rocha, & Timofeiczyk Junior, 2012; Rocha, 2002; Rocha & Tomaselli, 2001).

These results are supported by Murara Junior et al. (2013), as the main saw operator has greater responsibility in the sawmill's performance. On the other hand, dimensions of the products that will be generated by the main saw are defined by the saw edge and aligner machine operators, where saws with wider thicknesses which generate more residues are used. However, their decision on the width of the piece to be removed directly influences the yield obtained from log splitting (Manhiça et al., 2012).

Although the overall yield for the sawmill was less than 50%, the results shown in this work are better than the results obtained by other authors: Dutra, Nascimento, and Numazawa (2005), 32.30%; Clement and Higuchi (2006), 30%, Nascimento, Dutra, and Numazawa (2006), 36.50%; Cavallet, Oliveira, Arruda, and Acosta (2010), 35.18%, Pereira, Santos, Vedoveto, Guimarães, and Veríssimo (2010), 37%, Marchesan (2012), 29.88%, who also evaluated the yield of different commercial species in the Amazon. However, it was below the range of 45 to 55% suggested for hardwoods (Danielli et al., 2016; Gomide, 1974), and below the values observed by Oliveira, Martins, Scolforo, Resende, and Souza (2003), 49.28%; Souza (2006), 45.16%; and Biasi and Rocha (2007), 58.8%, who also studied the yield of tropical species.

In general, the yield volume of an Amazonian commercial species can vary from 40% to 65% (Gomide, 1974), meaning that approximately half the log is transformed into waste, and this often occurs depending on the type of wood and also the applied technologies (Mady, 2000;Souza, 2006). Considering the ten species studied, the average yield varied from 37% to 54.4%, being within the standard found in the study by Vidal, Barreto, Johns, Gerwing, and Uhl (1997) in evaluating a set of species and found the yield ranging from 25% to 70%.

Analysis by diametric classes facilitates an evaluation and influence of the log diameter on the minimum and maximum yield values, as well as the productive and operational process in the sawmill (Danielli et al., 2016; Melo et al., 2016). The logs of the same diameter class present yield values with low variation, and this trend remains when the class increase occurs. Some species such as *Dinizia excelsa* and *Handroanthus albus* suggest considering the stratification by medium diameter class once the use of sawn wood has decreased. However, the remaining eight species suggest that the yield is similar in different log diameter classes, with a slight decrease in yield for larger classes. In analyzing the yield of tropical species, Tonini and Ferreira (2004) also found a decrease in yield in larger diameter classes due to the occurrence of cracks, knots, protrusions rot in the studied logs. Other studies have also shown that yield per diameter class is also similar for commercial species such as *Manilkara huberi* (Danielli et al., 2016), *Erisma uncinatum, Qualea albiflora* and *Mezilaurus itauba* (Biasi & Rocha, 2007).

When considering yield averages among species, similar results were found for *Dipteryx odorata, Goupia glabra, Manilkara huberi* and *Carapa guianensis*. In addition to the trunk shape and profile which is more rectilinear in shape for these species (Carvalho, 2009; Costa, Carvalho, & Berg, 2007; Ferraz, Camargo, & Sampaio, 2002; Santos, 2002), the similarity in yield may also be related to the log dimensions found, even though the amount of sawed products is different. However, when the larger species such as *Dinizia excelsa* and *Vochysia guianensis* are considered, differences in yield are well-established.

For *Manilkara huberi*, which is the most commercialized species of the sawmill, the average yield obtained in this study was only 40.30%, but it is higher than the 30.1% found by Danielli et al. (2016). The yield value of this species may be related to straight grain logs, since it causes the release of growth stresses and drying the extremities extend the cracks, which ends up accounting for a considerable loss in log volume (Gerwing et al., 2001).

According to data from the International Tropical Timber Organization (Silva, Silva, & Cordeiro, 2012; ITTO, 2017), the production of sawn wood in the Amazon region has grown in recent years. For example, it was estimated that the volume of tropical sawn wood exports increased by 4.7% in volume from 32,200 m^3 in June 2016 to 33,700 m^3 in June 2017. However, according to the report presented by Hummel (Hummel et al., 2010), they still have a low average yield (41%). These data consequently suggest that huge amounts of wood are lost, often due to the sawmill infrastructure and lack of knowledge on the potential for various uses that the waste can offer (Braz, Nutto, Brunsmeier, Becker, & Silva, 2014).

In the sawmill under study, the waste destination is focused on producing coal and supplying small furniture industries (Pinheiro et al., 2004). As shown by Hummel et al. (2010), 24% of the waste in the sawmills of the Amazon region is used in different ways (in landfills, as a fertilizer, firewood, among others). Waste that is not used is burned or left as debris.

Pereira et al. (2010) also estimated the timber production of the Legal Amazon in 2009 with an average yield of 41% in processing. For Melo et al. (2016), the quantitative utilization of transforming a log into boards (considering a log with bark) occurs to the order of 40% of processed wood, with the remaining 60% being allocated as: 10% planer shavings, 26% cutter shavings, 13% sawdust and 11% bark.

The waste in the timber sector in the Amazon region is still very large, despite the technological advances. Only five for every ten trees cut will be used commercially (Mady, 2000; Pinheiro et al., 2004). Okai, Frimpong-Mensah, and Yeboah (2004) and Okai and Boateng (2007) also reported that almost 50% of the tree volume for each felled tree is left in the forest in the form of branches, crown, and stump. With this loss of wood resources in both exploitation/extraction and processing, it can be said that most industries are not contributing to their full potential and that environmental compensation services should be developed and applied to native forests.

Thus, new alternatives must be created for managing the sawn wood production and use of forest residues from the forest exploitation in several sectors, maximizing their use and minimizing the waste during the production chain from the harvesting to the end product (Braz et al., 2014).

Conclusions

In summary, the general yield obtained for the sawmill as well as the yield of each species is within the legal standards for the industry operations, being higher than 35% in all cases. There were no significant differences in diameter classes for the species except for *Handroanthus albus* and *Dinizia excelsa*. However, there was no significant linear increment between the diameter and yield of sawn wood for all species. The species *Dinizia excelsa, Hymenolobium petraeum, Ocotea rubra* and *Vochysia guianensis* show a significant difference in yield for the other species due to the higher obtained values, however, they are statistically similar when compared to each other.

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Conflicts of interest

The authors declare no conflict of interest.

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