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Articles

Volumetric stock classification of uneven-aged forests in the Eastern Amazon: a multivariate approach

Classificação do estoque volumétrico de florestas nativas na Amazônia Oriental: uma abordagem multivariada

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ABSTRACT

Although uneven-aged forest management is the most suitable method for conserving forests, the primary challenge in managing them lies in their heterogeneity, as commercial timber species are not evenly distributed. Therefore, classifying the volumetric stock of these forests into homogeneous areas is a strategic tool for implementing forest management. We aimed to compare distance measurements and clustering methods to classify the volumetric stock of an uneven-aged forest in the Eastern Amazon. We carried it out in the Tapajós National Forest, in an area corresponding to 79,084.67 ha of dense ombrophilous forest type. For the sample forest inventory, we installed 12 strips, with lengths ranging from 4.0 km to 19 km, spaced at 4.0 km intervals. In these strips, plots of 30 m x 250 m were systematically distributed. We selected trees with stem quality 1 (straight stem) and 2 (stem with small tortuosities) to classify the volumetric stock. We grouped the plots into homogeneous groups based on the combination of five distance measurements with eight hierarchical clustering methods. The cluster and discriminant analyses made it possible to gather the homogeneous plots in terms of volume, basic wood density, and marketing group. The combination of Manhattan distance measurement and the Ward2 method was the most efficient way to classify the forest into volumetric stock classes. These results are important to help fill research gaps related to uneven-aged forest management and allow these techniques to be applied in other forests around the tropics.

Keywords: Clustering; Discriminant analysis; Forest management

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RESUMO

Embora o manejo de florestas nativas seja o método mais adequado para a conservação florestal, o principal desafio reside na heterogeneidade das espécies, uma vez que estas não estão uniformemente distribuídas. Portanto, a classificação do estoque volumétrico dessas florestas em áreas homogêneas é uma ferramenta estratégica para a execução do manejo florestal. O objetivo deste estudo foi comparar medidas de distância e métodos de agrupamento para classificar o estoque volumétrico de uma floresta nativa na Amazônia Oriental. A pesquisa foi realizada na Floresta Nacional do Tapajós, em uma área correspondente a 79.084,67 ha de floresta ombrófila densa. Para o inventário florestal amostral, foram instaladas 12 faixas, com comprimentos variando de 4,0 km a 19 km, equidistantes a cada 4,0 km. Nessas faixas, foram distribuídas sistematicamente parcelas de 30 m x 250 m. Para a classificação do estoque volumétrico, foram selecionadas árvores com qualidade de tronco 1 (tronco reto) e 2 (tronco com pequenas tortuosidades). Agrupamos as parcelas em grupos homogêneos com base na combinação de cinco medidas de distância com oito métodos de agrupamento hierárquico. As análises de agrupamento e discriminante permitiram reunir as parcelas homogêneas em termos de volume, densidade básica da madeira e grupo de comercialização. A combinação da medida de distância de Manhattan e o método Ward2 foi a mais eficiente para classificar a floresta em classes de estoque volumétrico. Esses resultados são importantes para ajudar a preencher lacunas de pesquisa relacionadas ao manejo de florestas com árvores de diferentes idades e permitem que essas técnicas sejam aplicadas em outras florestas nos trópicos.

Palavras-chave: Agrupamento; Análise discriminante; Manejo florestal

1 INTRODUCTION

Brazil has the second-largest forest cover in the world, encompassing approximately 486.1 million hectares and accounting for about 12% of the global forest area (FAO, 2025a), reflecting its importance for forest conservation. In addition, the Amazon biome is the largest and most representative biome in Brazil, covering approximately 49.5% of the national territory (Mapbiomas, 2025) and encompassing extensive forest areas with high potential for sustainable forest management and timber production (FAO, 2025b).

However, the main difficulty in managing natural forests in the Amazon is that their production areas are heterogeneous, with no regular distribution of commercial timber species across all subdivisions of an Annual Production Unit (APU) (Braz et al., 2004).

Since knowledge of a forest's structural characteristics is fundamental to managing it sustainably (Ziembowicz et al., 2024), an alternative to minimize

this problem is to classify the forest's volumetric stock, defined as the available commercial wood ($m^3.ha^{-1}$). This is one of the basic requirements of the Forest Management Plan (PMF) in Brazil (Ministério do Meio Ambiente, 2006; Souza; Souza, 2006). This stock considers the results of the APUs' 100% forest inventory and the criteria for selecting trees for logging in the Annual Operational Plan (AOP) (Ministério do Meio Ambiente, 2006).

Nevertheless, the heterogeneity of the forest means that in some places the capacity to replenish the stock of harvested commercial timber is underestimated, harming the productive sector. In others, it is overestimated, leading to the compromise of the volumetric stock of the forest (Braz et al., 2015).

Due to the high wood variability of the upland equatorial forest, its classification into areas with more homogeneous volumetry allows for inferring the volumetric potential of each class or site and supporting the elaboration and execution of forest management plans (Souza; Souza, 2006).

This classification can also generate economic and ecological benefits, as it provides subsidies for better infrastructure and tactical and operational planning, reducing costs and increasing profitability. In addition, the gain in efficiency has less impact on the remaining vegetation (Souza et al., 1990).

Multivariate statistical techniques are widely used in forest science, as they group similar features and separate distinct ones (Bowling; Zelazny, 1992; Pio et al., 2023; Felix et al., 2023). Therefore, they are useful tools when evaluating the productivity of uneven-aged forests and can be successfully used to classify and order homogeneous groups (Vanclay, 1992).

Multivariate techniques of cluster and discriminant analysis are important for forest management, due to their feasibility for the classification of volumetric stock in uneven-aged forests (Webb et al., 1967; Webb et al., 1971; Souza et al., 1990; Ferreira; Souza, 1997; Souza; Souza, 2006; Arruda, 2008; Lima et al., 2014; Souza et al., 2014; Silva et al., 2015; Corrêa et al., 2018; Pereira et al., 2019). However, among the various

clustering methods and distance measurements to form clusters, it is important to carry out studies to define the most appropriate combination of methods and measurements for uneven-aged forests.

In this context, we hypothesized that the choice of distance measure and clustering method influences the classification of volumetric stock in an uneven-aged forest. Thus, we aimed to compare distance measurements and clustering methods to classify the volumetric stock of an uneven-aged forest to be managed in the Eastern Amazon.

Given the importance of accurate forest resource assessment for management planning, this study is consistent with the objectives of the United Nations Sustainable Development Goal 15 (SDG 15), particularly those related to the sustainable management of forests.

2 MATERIALS AND METHODS

2.1 Study area

This study was conducted in the Tapajós National Forest, a Conservation Unit covering approximately 527,319 hectares (ICMBio, 2019), located in the western part of the State of Pará, Brazilian Amazon.

According to the Koppen classification, the climate of the region is of the Am type, characterized as a tropical climate with an average temperature of the coldest day of the year above 18°C. The concentration of rainfall occurs between January and May, with an average annual rainfall of 1,820 mm (Alvares et al., 2013).

The relief varies from gently undulating to undulating, with a predominance in the area of the Dystrophic Yellow Latosol type, characterized by being deep and with low cation exchange capacity (IBAMA, 2004; De Oliveira Junior et al., 2015).

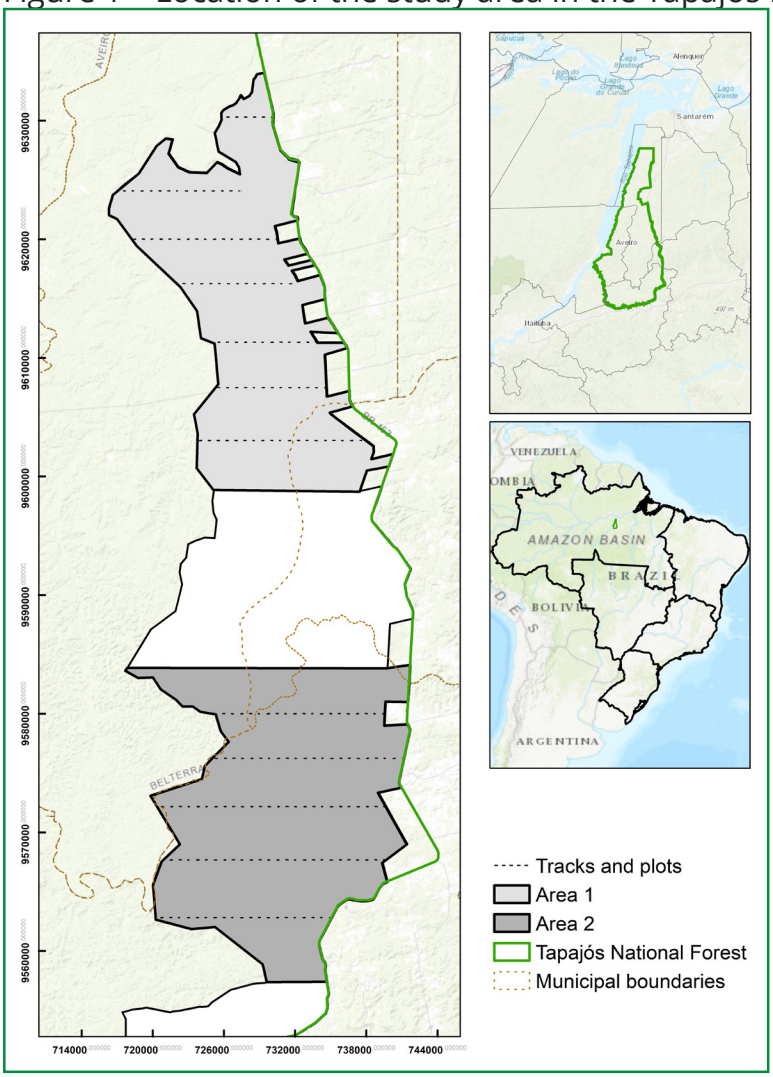
In northern Brazil, the Tapajós National Forest is located in the Dense Ombrophilous Forest zone, a type of vegetation characterized by the dominance of large trees, high temperatures, and intense rainfall distributed throughout the year, with a dry period lasting up to 60 days (IBGE, 2012).

2.2 Data collection

We installed the plots in a forest initially established as a Non-Timber Forest Management Zone (IBAMA, 2004). However, a forest inventory was carried out to meet a demand from the Chico Mendes Institute for Biodiversity Conservation (ICMBio), the unit's managing body, to change the zoning of the Conservation Unit, and since then, this area has become a Forest Management Zone (ICMBio, 2019).

The inventoried stretch corresponds to two areas of predominance of the Dense Ombrophilous Forest typology, located on the banks of the BR-163 highway, in the municipalities of Belterra and Rurópolis, state of Pará (Zone 21M, Lat.: 3°18'23.41"S - Long.: 54°56'44.77"W, Datum WGS 84) (Figure 1).

Figure 1 – Location of the study area in the Tapajós National Forest, Eastern Amazon



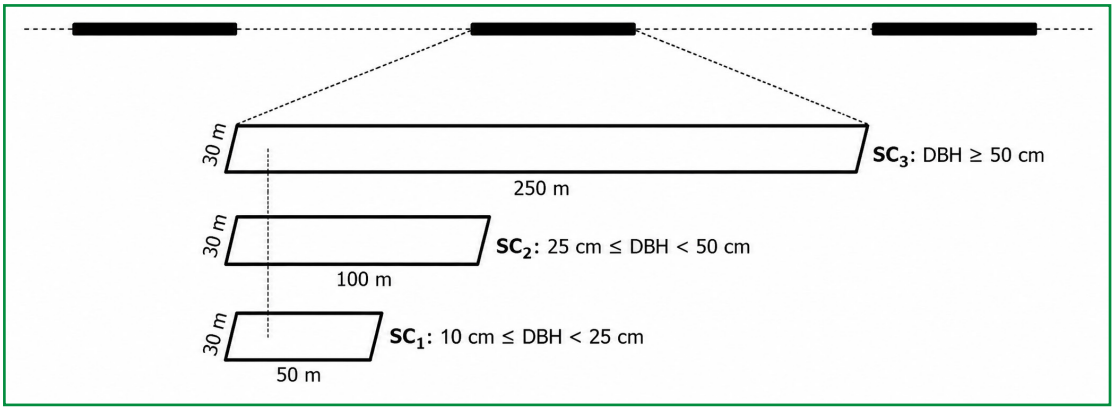
Source: Authors (2026)

The areas are situated in a region with varying topographic conditions (high and low plateaus), featuring emergent trees and separated by a section of land with a steep slope. Area 1 has 36,925.33 ha, and Area 2 has 42,159.34 ha, totaling 79,084.67 ha (Andrade et al., 2015).

We installed 12 strips of approximately 1.5 m wide, equidistant 4 km, in an east-west direction, with lengths ranging from 4 to 19 km. The plots were installed systematically, with dimensions of 30 m x 250 m, spaced by 500 m in each strip. There were 94 plots in area 1 and 110 in area 2, totalling 204 plots. The sample was 154.5 ha, which represented a sampling intensity of 0.193% (Andrade *et al.,* 2015).

We measured the trees in the plots, considering the DBH (diameter at breast height - at 1.3 m from the ground) in the following size classes (SC): SC 1 (regeneration class) – 10 cm ≤ DBH < 25 cm in the first 50 m of the plot (30 m x 50 m); SC 2 (pre-harvest class) - 25 cm ≤ DBH < 50 cm in the first 100 m (30 m x 100 m); and SC 3 (harvest class) - DBH ≥ 50 cm in the entire plot (30 m x 250 m) (Figure 2).

Figure 2 – Plots and the size class (SC) identification of the inventoried trees in the Tapajós National Forest



Source: Authors (2026)

During the inventory, we recorded the following variables: species; DBH; commercial height, visually estimated by the method of superposition of equal angles (Silva; Paula Neto, 1979); and stem quality (QF), being classified as straight stem (1);

stem with small tortuosities (2); and non-commercial stem (3).

We identified the trees based on a specialized bibliography, produced from forest inventories carried out by the Brazilian Agricultural Research Corporation (Embrapa Eastern Amazon), with an updating of scientific names from virtual lists of Brazilian flora (Andrade et al., 2015).

We adopted the Angiosperm Phylogeny Group (APG) IV (The Angiosperm Phylogeny Group, 2016) botanical classification system to present the taxa. We confirmed the spelling of the species names in the Missouri Botanical Garden database (Missouri Botanical Garden, 2014).

2.3 Data analysis

2.3.1 Determination of volume (m^3), basic wood density ($g.cm^{-3}$) and marketing group of species

We selected the commercial species with DBH ≥ 50 cm and stem quality 1 and 2 to calculate their volume (m^3), and to determine their basic wood density ($g.cm^{-3}$), and marketing group, according to Gama et al., (2009). From the dendrometric variables collected, we estimated the volumes of stems with tree bark by the form factor equal to 0.70 (Heinsdijk; Bastos 1963; Brasil, 2015).

We classified the commercial timber species by basic wood density into species with heavy (≥ 0.73 $g.cm^{-3}$), medium (0.51 < $g.cm^{-3}$ < 0.72), and light density (≤ 0.50 $g.cm^{-3}$) (Melo et al., 1990). The basic density values of each species were based on the works of Lobato (1969), Detienne et al. (1982), Detienne and Jacquet (1983), Fearnside (1988), Souza et al. (2002), Nogueira et al. (2005), Quirino et al. (2005), Silva (2006), Lorenzi (2008), and Silva et al. (2015).

In addition, we also classified the commercial timber species according to their MG (marketing group), based on the selling price of the wood and its features (Gama et al., 2007), in which the respective categories were defined as MG 1 = special woods;

MG 2 = noble woods; MG 3 = red woods; MG 4 = mixed woods; and MG 5 = white woods (Table 1). All timber prices were adjusted to 2025 values using the National Broad Consumer Price Index (IPCA), Brazil's official inflation index.

Table 1 – Categories of species found in the area of the Tapajós National Forest according to their marketing group (MG). Adapted from Gama et al., (2007)

Code	Marketing Group	Features	Price (R$.m^{-3})
MG 1	Special woods	Wood that is prone to extinction and/or has a high value in the regional, national, and international markets.	346.31
MG 2	Hardwoods	Wood sold in the regional, national, and international markets.	259.74
MG 3	Red woods	Wood sold in the regional and national markets.	173.14
MG 4	Mixed woods	Commercial hardwood, saw, and blade.	86.57
MG 5	White woods	Commercial woods, saw, and blade, soft.	43.28

Source: Authors (2026)

2.3.2 Volumetric stock classification

We used the size class 3 data, as it is the class that encompasses the trees that are part of the harvesting stock, respecting the minimum logging diameter of 50 cm, as established by Brazilian current legislation (Brasil, 2006; SEMAS, 2015).

Thus, we gathered the estimated volumes of commercial stems with tree bark by plot and in each of the basic density classes and marketing groups. X matrices were elaborated for these volumes, in which each Xijh represented the volume of the i-th plot, in the j-th density class, and in the h-th marketing group, and this matrix was used as input for the clustering and discriminant analyses.

For the construction of the similarity matrix, we concatenated the density classes with the marketing groups to which the plants belonged. In this way, the trees have the same information to these two variables, that is, trees that belonged, for example, to density class 1 (C1) and to marketing group 3 (G3), now belong to the same class, which in this case is C1G3.

Thus, we constructed a similarity matrix from a dynamic table in an electronic spreadsheet, in which the plots were allocated in the command lines, the new categorization of density class with marketing group in the columns, and the volume values (m^3) of the individuals in the field corresponding to the values.

The 204 plots were grouped into homogeneous groups, in which 40 vertical dendrograms were produced, based on the combination of 5 distance measurements (Euclidean, Squared Euclidean, Manhattan, Canberra, and Mahalanobis), with 8 hierarchical clustering methods (Ward1, Ward2, Single Link, Complete Link, UPGMA (Unweighted Pair-Group Method with Arithmetic mean), WPGMA (Weighted Pair-Group Method with Arithmetic mean), Median, and Centroid).

Among the clustering methods, we used two different algorithms for Ward's method - Ward1 and Ward2 (Murtagh; Legendre, 2014). Both are found in the literature and in software, announcing that both implement Ward's method (Ward, 1963), but when applied to the same distance matrix, they produce different results.

Each measure of similarity calculated with each clustering method produced dendrograms, which served as a basis for interpreting the results and defining the structure of the data. In addition, we compared the most appropriate method, using the best distance measurement for the definition of the forest volumetric stock classes.

In each dendrogram, a phenon line (line parallel to the horizontal axis of the dendrogram) was drawn at the point where the formation of three distinct groups was observed, representing the high, medium, and low stock classes. The dendrograms are read from right to left, in which the vertical lines (y-axis) indicate the distances between the formed clusters, and the position of the line on the scale (x-axis) represents the clusters joined in descending order of similarity.

To verify the validity of the clustering methods, we constructed 40 Fisher's linear discriminant analysis tables, one for each combination of the tested methods. These tables contain the percentage of combinations classified in the cluster analysis and the classification probabilities for each stock class. We performed cluster analysis using

the vegan package (Oksanen et al., 2016) and discriminant analysis using the MASS package (Venables; Ripley, 2002) in R version (R Core Team, 2019), with support from the RStudio platform version 0.97.

The comparison between the methods considered not only the results of the discriminant analyses but also the operational planning of the harvest. Thus, with the best combination of methods, volumetric stock classes were established in 3 different stock levels (high, medium, and low).

3 RESULTS

A total of 10,578 trees belonging to 238 species and 62 families were sampled throughout the area. After the filter aiming only at the presence of commercial trees that have stem quality 1 and 2, 7,838 trees remained, of which 3,147 were present in SC 1 (10 cm ≤ DBH < 25 cm), 2,554 in SC 2 (25 cm ≤ DBH < 50 cm), and 2,137 trees in SC 3 (DBH ≥ 50 cm).

3.1 Determination of the best combination of methods for classifying volumetric stock

To select the most appropriate method, we found through discriminant analysis that, out of the 120 combinations tested across the 3 size classes, only 35 achieved 100% accuracy in grouping, with 12 combinations being common to all 3 size classes: Euclidean (with UPGMA, Median, and Centroid) and Manhattan (with WPGMA).

However, none of these combinations were considered, as each had at least one stock class with only a single plot, which, in practice, makes forest management technically unfeasible (Table 2).

Thus, a visual analysis of the dendrograms was performed, leading to the selection of the Euclidean method with Ward1 (Figure 3) and the Manhattan method with Ward2 (Figure 4), based on the homogeneity of plot numbers across volumetric stock classes compared to the other methods.

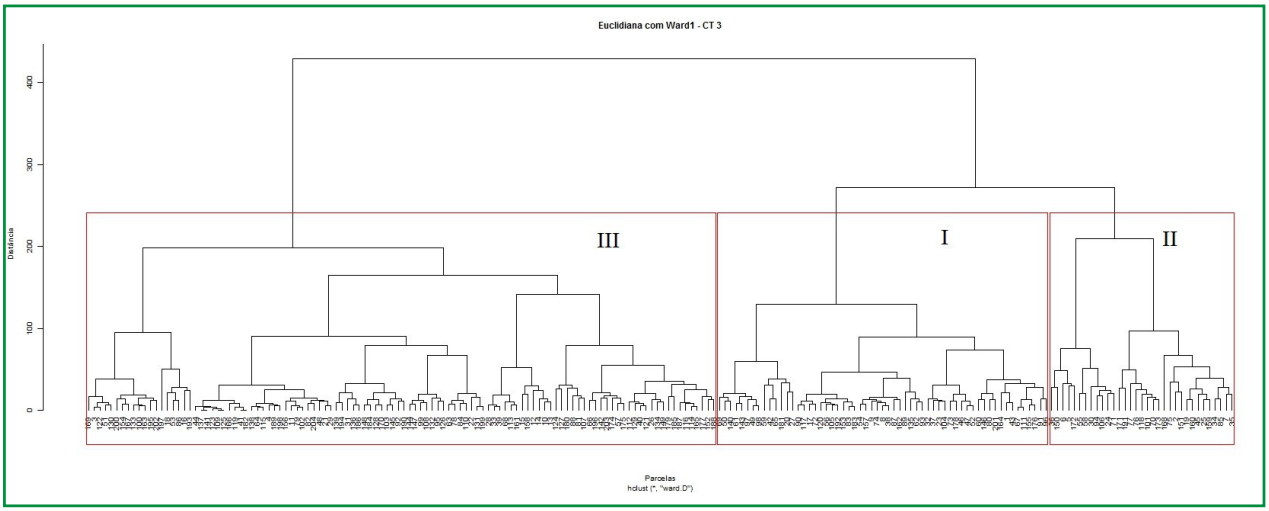
Table 2 – Combination of methods that obtained 100% accuracy in the 3 size classes and the number of plots classified in classes I, II, and III

SC	Distance measurement	Clustering Method	VSC I	VSC II	VSC III
SC 1	Euclidean	UPGMA	1	199	4
		Median	1	1	202
		Centroid	1	202	1
	Manhattan	WPGMA	1	3	200
SC 2	Euclidean	UPGMA	1	199	4
		Median	1	1	202
		Centroid	1	1	202
	Manhattan	WPGMA	2	1	201
SC 3	Euclidean	UPGMA	1	1	202
		Median	1	1	202
		Centroid	1	1	202
	Manhattan	WPGMA	9	1	194

Source: Authors (2026)

In where: SC= Size Class; VSC = Volumetric Stock Class = number of plots classified in classes I, II, and III

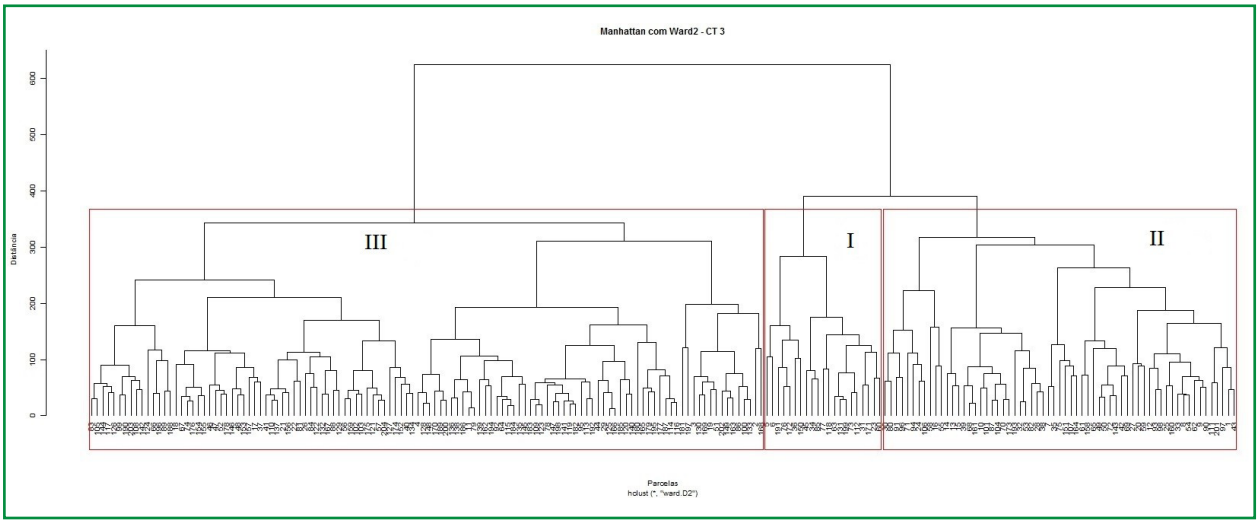
Figure 3 – Dendrogram generated from cluster analysis using the Ward1 method with Euclidean distance for the trees in size class 3 in the Tapajós National Forest



Source: Authors (2026)

In where: I, II, and III = volumetric stock classes.

Figure 4 – Dendrogram generated from cluster analysis using the Ward2 method with Manhattan distance for the trees in size class 3 in the Tapajós National Forest



Source: Authors (2026)

In where: I, II, and III = volumetric stock classes.

Among these combinations, the Manhattan and Ward2 combinations stand out because more than half (50.23%) of the plots present in stock class I using the Manhattan distance are common in stock class I of the Euclidean distance (Table 3).

Table 3 – Mean percentages of correct classification in the methods that used distance measures with Ward1 and Ward2 common in the 3 size classes of the Tapajós National Forest

Distance measure	Ward (%)	Ward2 (%)	SC 1			SC 2			SC 3		
			I	II	III	I	II	III	I	II	III
Euclidean	90.83	-	132	48	24	117	33	54	59	33	112
Manhattan	-	89.36	95	43	66	82	53	69	20	65	119

Source: Authors (2026)

In where: Ward and Ward2 = Means of the percentage of correct classification by the methods of Ward1 and Ward2 in the 3 size classes; SC = Size class; I, II, and III = number of plots classified in classes I, II, and III of volumetric stock.

Based on the grouping obtained using the Manhattan distance with Ward2, volumetric estimation by size class and stock class was conducted to define classes I, II, and III. Class I represents the most productive volumetric stock, followed by class II with medium productivity and class III with the least productivity (Table 4).

Table 4 – Characterization of the volumetric stock classes by size class in the Tapajós National Forest

Variables	Unit	SC 1			SC 2			SC 3		
		I	II	III	I	II	III	I	II	III
Density	$n.ha^{-1}$	34.57	34.41	33.85	17.74	13.46	10.52	8.25	2.83	2.89
Basal area	$(m^2.ha^{-1})$	0.81	0.79	0.80	1.75	1.30	1.02	3.42	1.22	1.12
Volume	$(m^3.ha^{-1})$	5.21	4.95	4.83	14.46	10.43	8.20	37.88	14.13	11.96

Source: Authors (2026)

In where: SC = Size Class; I, II, and III = volumetric stock classes

3.2 Classification of the volumetric stock

Using only the data from size class 3, by combining the Manhattan with Ward2, we observed that the consistency of the classification of the plots in the respective stock classes had a percentage of correct answers by discriminant analysis of 93.1% (Table 5).

Table 5 – Final result of the discriminant analysis with the classifications (%) and the probabilities of classification (I P, II P, and III P) of the plots in the volumetric stock classes in the Tapajós National Forest

DM/CM	VSC	Classification into Stock Classes			Total	Classification (%)
		I P = 0.10	II P = 0.31	III P = 0.59		
Manhattan/Ward2	I	20	0	0	20	100
	II	1	57	7	65	87.7
	III	0	6	113	119	95
	Total	21	63	120	204	93.1

Source: Authors (2026)

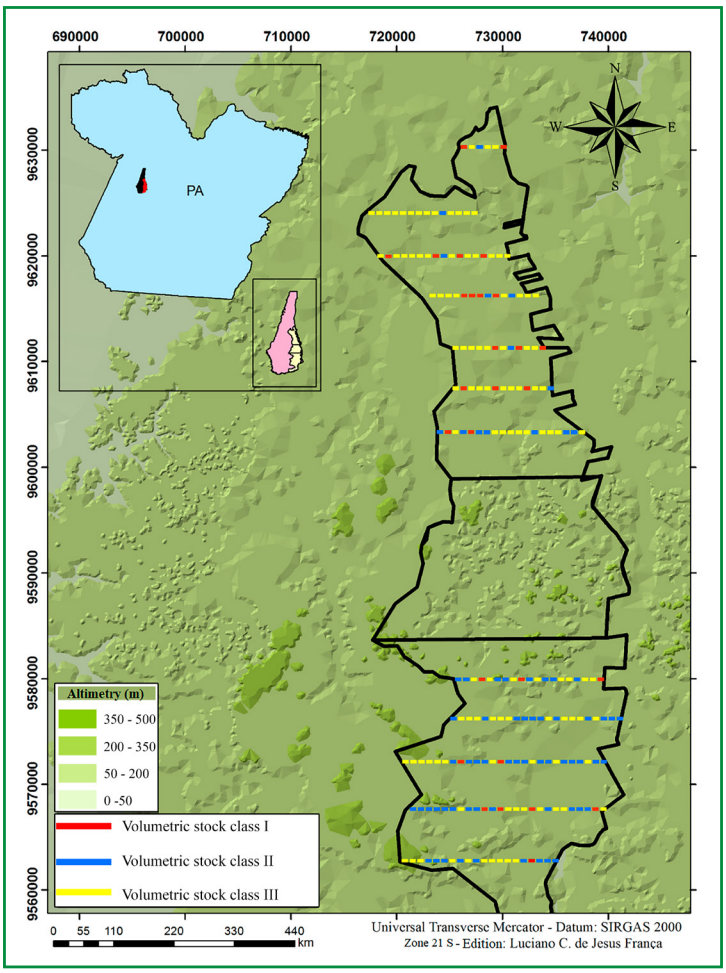
In where: DM= Distance measure; CM = Clustering method; VSC = Volumetric Stock Class

Thus, we classified each plot according to its volumetric stock class (Figure 5) and then performed a spatial representation of the volumetric stock classification (Figure 6), considering the operability of forest management activities. This clustering involves subjective spatialization, as it incorporates the visual analysis of the productive classification of the plots and the forest manager's experience.

Summing the sizes of all the areas within the volumetric stock classes described in Figure 5, we obtained 12,119.12 ha for volumetric stock class I, 34,031.74 ha for class II, and 32,933.81 ha for class III, resulting in a total of 79,084.67 ha of sampled and classified area.

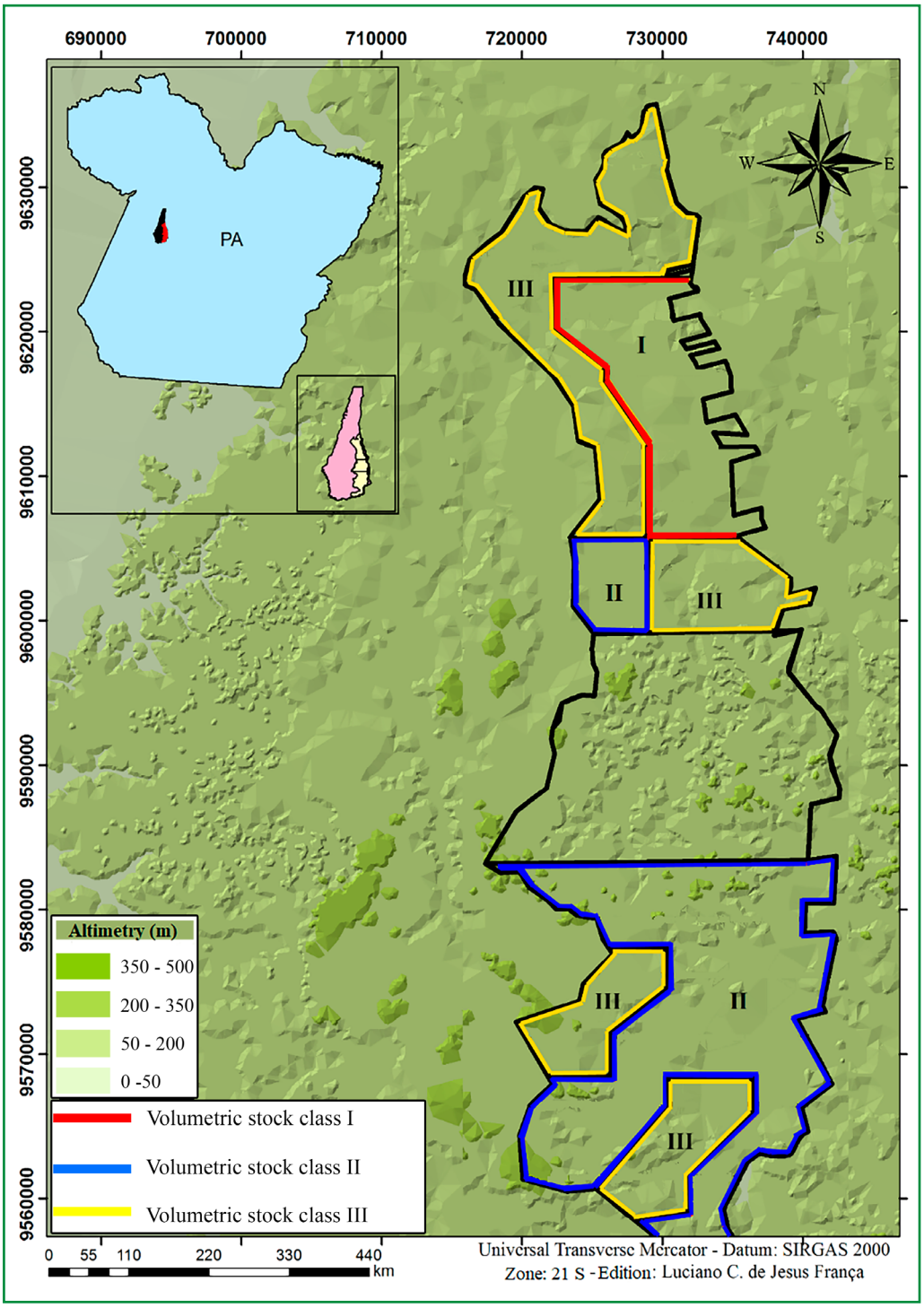
In the characterization of each volumetric stock class, the sum of the volumes, considering the size of each class, was approximately 5659 m³, 4233 m³, and 2380 m³, for stock classes I, II, and III, respectively (Table 6).

Figure 5 – Volumetric stock classes I, II, and III from the clustering performed by combining the Manhattan distance measure with Ward2 in the Tapajós National Forest



Source: Authors (2026)

Figure 6 – Clustering of volumetric stock classes, defined by combining the Manhattan distance with the Ward2 clustering method, in the Tapajós National Forest



Source: Authors (2026)

Table 6 – Characterization of the volumetric stock classes, showing the minimum average, maximum volumes, the standard deviation, and the coefficient of variation by stock class in the harvest size class (SC 3)

Volumetric Stock Classes	Volume (m³)				
	Minimum	Medium	Maximum	Deviation - Standard	Coefficient of Variation (%)
I	105.30	158.9	232.06	37.50	23.60
II	85.31	144.81	223.06	31.75	21.93
III	5.17	86.67	186.22	32.21	37.16

Source: Authors (2026)

4 DISCUSSION

4.1 Best match between distance measure and clustering method

The present study supports the hypothesis that the classification of volumetric stock in uneven-aged forests is sensitive to the combination of distance measures and clustering algorithms employed. The observed differences in the characteristics of each class indicate that methodological choices can substantially affect the representation of forest variability. Consequently, the selection of clustering procedures should not be regarded as a merely computational step, since it directly influences the ability of the resulting classes to capture meaningful patterns in forest structure and growing stock distribution.

None of the methods that achieved 100% accuracy in discriminant analysis classification were selected, as the ideal scenario requires approximately equal numbers of plots in each stock class. This ensures that the execution of harvesting activities outlined in the forest management plan is more feasible, both in terms of operational efficiency and optimization.

Only the combinations involving the Ward1 and Ward2 methods yielded the desired classification with respect to the number of plots per stock class. This is

because Ward's method tends to produce clusters with approximately equal numbers of observations, making it a recommended technique when the researcher aims for cluster patterns that reflect groups of similar size (Hair et al, 2009).

Although the Euclidean method with Ward1 presented a higher cluster validation score compared to the Manhattan method with Ward2, the difference was minimal. This led to the selection of the distance measurement and clustering method combination that grouped the plots more homogeneously within each volumetric stock class.

In SC 3 (harvest class) of the Euclidean with Ward1 and Manhattan with Ward2 combinations, the second method is more feasible. In addition to the plots being quite similar in each stock class for both methods, the number of plots in the most productive class is smaller, which would reduce the costs of installing the plots in the field while achieving similar results in terms of volumetric stock.

Although the distance from Manhattan to the Ward2 cluster was selected to rep-resent the classification of the forest under study, we noted that the Euclidean method with Ward1 was also effective in terms of validating the cluster, as can be seen in the studies by Souza et al., (1990), Souza and Souza (2006), Arruda (2008), Lima et al., (2014), and Souza et al., (2014).

However, it is recommended that future studies on the classification of the productive capacity of uneven-aged forests adopt the Manhattan distance measure and compare it with other metrics to enhance the distinction between the formed groups. Its practical adoption depends on ease of interpretation, clustering stability, and the ability to generate classes that can be effectively incorporated into the operational planning of forest management units.

Additionally, assessing the coefficient of variation of volumetric stock within classes can provide further insight into classification quality, as successful stratification is expected to reduce within-class variability. It is also important to examine the distribution of sampling units among classes, since extremely small or overly large classes, despite being statistically acceptable, may be difficult to incorporate into operational management planning and decision-making processes.

4.2 Classification of volumetric stock

Although there are techniques for defining the number of groups formed, there is no standard and objective selection procedure (Bock, 1985; Hartigan, 1985), allowing the researcher to select the solutions that best represent the data structure (Hair et al., 2009). Even when empirical measures are used as a consensus, the researcher should complement empirical judgment with a conceptual understanding of theoretical relationships that may suggest a natural number of clusters, while considering criteria based on practical considerations (Hair et al., 2009).

Thus, regarding volumetric stratification of uneven-aged forests, it is recommended that three stock classes be defined (Souza; Souza, 2006; Arruda, 2008; Lima et al., 2014; Souza et al., 2014; Silva et al., 2015; Corrêa et al., 2018; Pereira et al., 2019). This number allows the identification of areas of high, medium, and low production, in addition to providing subsidies for decision-making by the manager, aiming at better tactical and operational planning of forest harvesting, such as determining the number of workers, the number of teams, and the size of infrastructures, among others (Silva et al., 2015).

The discriminant analysis is a useful technique not only to assess cluster consistency but also to allocate data to groups with greater statistical affinity (Medeiros 2008). This means that the plots showed similar volumetric characteristics within the group to which they belong, and heterogeneity between the groups formed.

The classification of the volumetric stock in the study area allows the manager to plan the specific intervention levels for each stock class, such as the application of silvicultural treatments, harvesting activities, and monitoring of the managed forest (Souza et al., 2014), allowing operations planning to be tailored to the characteristics of each class. By generating more homogeneous volumetric stock classes, this classification approach can help identify areas with greater productive potential and support decision-making regarding harvesting priorities, road planning, and operational logistics, thereby improving the efficiency of forest management activities in the Brazilian Amazon.

Furthermore, by reducing uncertainty in stock estimates and providing a more objective basis for decision-making, such approaches can contribute to sustainable forest management and align with Environmental, Social, and Governance (ESG) principles, particularly those related to environmental stewardship and governance through improved resource allocation, transparency, and long-term conservation of forest resources.

5 CONCLUSION

The Manhattan distance measurement and Ward2 clustering method were the most efficient for stratifying inequitable forests into volumetric stock classes in the lower Tapajós River region.

The cluster and discriminant analyses allowed us to stratify the heterogeneous plots into 3 stock classes and thus define homogeneous areas in terms of volume, basic wood density, and marketing group.

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