

Article

Alternative Tree Species for Sustainable Forest Management in the Brazilian Amazon

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Abstract: The scarcity of hardwoods from tropical forests makes the search for alternative species necessary for commercialization. This study aimed to establish groups of timber species from the Amazon Forest with potential for logging purposes through the assessment of their physical-mechanical properties, aiming to identify alternative species that can meet the market demands. We utilized data from the Forest Products Laboratory (LPF) (containing information on basic density and other wood mechanical properties) and the Timberflow platform, as well. We applied a multivariate cluster analysis technique with the aim of grouping species based on the technological characteristics of their wood and evaluating similarity among them to obtain homogeneous groups in terms of economic potential and utilization. The results indicated four homogeneous groups: Cluster 1 (40.72% of species, basic density-db: 690 kg m⁻³), Cluster 2 (13.92%, db: 260 and 520 kg m⁻³), Cluster 3 (27.32%, db: 550 and 830 kg m⁻³), and Cluster 4 (18.04%, db: 830 kg m⁻³). Most of the 20 listed species are classified as more commercially viable (70%), with high wood density. Species identified as alternatives include *Dialium guianense* and *Zollernia paraensis* for *Dipteryx odorata*, *Terminalia argentea* for *Dinizia excelsa*, *Terminalia amazonia* and *Buchenavia grandis* for *Goupia glabra*, and *Protium altissimum* and *Maclura tinctoria* for *Hymenaea courbaril*. The analysis highlighted the overexploitation of a restricted group of species and the need to find alternatives to ensure the sustainability of forest management. This study contributed to identifying species that can serve as alternatives to commercial ones, promoting a more balanced and sustainable forest management.

Keywords: alternative species; wood density; forest management; selective logging; cluster analysis; physical-mechanical properties



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1. Introduction

Natural forests provide multiple ecosystemic and socioeconomic services, as well as holding a significant portion of Earth's biodiversity [1–3]. Among the various services provided by this type of vegetation, timber production stands out, with tropical forests being an important source of timber supply for the world [4]. Brazil presents the largest area covered by tropical forests worldwide, particularly the Amazon Rainforest, which has been predominantly exploited through conventional logging practices characterized by minimal operational planning and low-impact mitigation [5,6].

In this context, the sort and intensity of polycyclic forest management are the main drivers of structural diversity and modulators of biodiversity in forest ecosystems [5,7]. Therefore, even reduced-impact logging can have effects, sometimes deleterious, on the abundance and composition of tree species [5]. Consequently, such practices impact the quantity and financially undermine the feasibility of timber extraction in future harvests [7,8].

Timber from tropical tree species is recognized for its distinctive physical and aesthetic characteristics, and is widely used in the manufacture of high-end furniture, flooring, cladding, decking, boats, musical instruments, and a wide range of handcrafted products [9]. Consumption and, consequently, the increase in demand for this type of forest resource is correlated with global economic growth, influenced by urbanization, increasing wealth, changes in design trends, and consumer preferences for wood-based products [10]. Such specific market preferences have driven the selective over-exploitation of a greatly restricted group of species in the Amazonian tropical forests [11,12].

Despite the economic advantages attributed to this very select group of timber species, their intense exploitation can lead to a lack of diversification in selective logging since the growth rate of these species does not keep pace with the market needs [13]. As a result, this lack of species diversification, together with their intense exploitation, can lead to a drop in the abundance and even the extinction of such species [14]. In addition, the low commercialization value resulting from the species composition and the small size of the trees harvested can make forest management financially unfeasible in later cycles [8].

Thus, the concentration of logging practices of certain groups of tropical species and the consequent overexploitation of these groups continues to be a worrying issue, as it weakens and negatively impacts logging in the Amazon [15]. An example of the effects of overexploitation, historically known, is the pau-brasil (*Paubrasilia echinata*), a species that was considered threatened with extinction in the 20th century [16]. This species is currently used to make jewelry, pens, and violin bows, and is considered an incorruptible wood as it does not rot and is resistant to insect attack [17].

In addition to pau-brasil, Brazilian mahogany (*Swietenia macrophylla*) is used in furniture manufacturing due to its ease of processing, dimensional stability, and durability [18]. Other species, such as Brazil nuts (*Bertholletia excelsa*) and rosewoods (*Dalbergia nigra* and *Aniba rosaeodora*), are highly valued in the market. However, due to their desirable characteristics and high international demand, these species have been severely exploited and are now considered endangered in Brazil [19]. Because of their overexploitation, all species of the genus *Handroantus*, *Tabebuia*, and *Dipteryx* will become part of the Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) as of November 2024 [20].

Currently, even if a broad and stable forest base were established for the regional timber industry, it would have to evolve substantially in terms of using greater volumes of a wider range of commercial species, as well as investing in technology and the development of new products [21,22]. From this perspective, species composition is an important aspect of the viability of forest management, and expanding this composition is a necessary factor to ensure the long-term sustainability of the activity [23].

Therefore, the scarcity of hardwoods makes it necessary to search for alternatives, specifically the discovery of new individuals for exploitation with similar characteristics. This explains the variation in species exploited each year and underscores the importance of conducting research to uncover the potential, whether for timber or other purposes, of native species in the Amazon [8], considering that the Atlantic Forest biome has already experienced overexploitation of forest species. To promote this substitution, it is crucial to survey the forest structure and its behavior concerning diameter distribution. Studies on the technological characteristics of woods intended for commercialization from alternative species [24] are also essential to assess the feasibility of using such species as alternatives and/or complements to intensively exploited species.

The construction and dissemination of this information is fundamental to the discovery of new timber species. It is also necessary to compare this information, especially on the

technological characteristics of the wood. That said, the aim of this study was to build groups of timber species from the Amazon rainforest, analyzing them based on their physical-mechanical properties, and thus, carry out a discriminant analysis to indicate timber species that could be alternatives to the commercial species that are in demand by the consumer market.

2. Materials and Methods

2.1. Database

The database of the Forest Products Laboratory (LPF), a center specializing in research, development, and innovation that performs activities in the areas of technology and the use of forest products, biomass energy, biotechnology, botany, toxic analysis of extractives, spectroscopy, wood structures, and construction processes, was used to build the groups of species with exploitation potential, toxicological analysis of extractives, spectroscopy, wood structures and construction processes, as well as providing support to agencies that oversee and control the timber trade, transport and exploitation, such as the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA), the Federal Police, the Environmental Police and State Environment Secretariats. The LPF is part of the structure of the Brazilian Forest Service, an agency linked to the Ministry of the Environment and Climate Change (MMA).

The properties that were analyzed are:

- Basic density (kg/m^3);
- Tangential shrinkage (%);
- Volumetric shrinkage (%);
- Radial shrinkage (%);
- Shear strength (MPa);
- Parallel hardness (kgf);
- Transverse hardness (kgf);
- Tensile strength (MPa);
- Flexural strength (MPa);
- Static bending (MPa);
- Compression at break (MPa);
- Proportional compression (MPa).

To identify the possible alternative species, we used quantitative information about the volume production of the proposed species, taken from the databases of the official forestry control systems stored on the Timberflow platform. These data mainly include forestry guides (for the transportation, sale, and processing of wood and other products) made available by IBAMA through the DOF/SINAFLO system, SISFLORA Mato Grosso, and SISFLORA Pará for the period between January 2007 and December 2020. In addition, the forestry company Cemal provided a list of the most exploited species in its Forest Management Unit (FMU). A list was generated of all the species traded at least once during this period. We then applied four criteria to segregate the most promising species, which must have the following characteristics:

(1) They are abundant in the forest: This criterion is important to avoid species that are rare in production forests or that exist endemically in one or a few regions of the Amazon. As a basis, we used the list of 227 naturally dominant forest species in the Amazon rainforest.

(2) Non-threatened: We selected species that, in addition to not presenting legal impediments to their exploitation, are not included in current ordinances on threatened species (IN MMA 01/2014, Ordinance MMA 443/2014, Ordinance MMA 561/2021), in addition to the CNCFlora and IUCN red lists.

(3) They are currently under-exploited: We selected, from the databases of the official forestry control systems, the species that have a low commercialized volume, defined as those that are not among the 20 main timber species in the Amazon which, as discussed above, account for half of the volume of the timber managed.

(4) They have their properties mapped: We considered species that present technical studies already conducted by reference research institutions, such as the LPF and the Institute of Technological Research (IPT), avoiding the disclosure of species for which little information is available to buyers and market operators.

2.2. Data Analysis

We used a multivariate cluster analysis aiming to group the species (based on their timber technological characteristics) and to assess the similarity between them in order to obtain homogeneous groups in terms of economic potential and use. An X-matrix of the data on these technological characteristics was drawn up, in which each variable x_{ij} represented the i -th technological characteristic classified in the j -th species.

The group resulting from this classification must exhibit high internal homogeneity (within-cluster) and high external heterogeneity (between-cluster). The X-matrix was used as an input in the cluster and the discriminant analyses. The simple Euclidean distance and Ward's method were used to separate the groups, applying the Equation (1):

$$d_{ij} = \sqrt{\sum_{k=1}^p (x_{ik} - x_{jk})^2} \quad (1)$$

where d_{ij} is the Euclidean distance between species i and j , and x_{ik} and x_{jk} are the values of the k -th technological characteristics of species i and j , respectively. Ward's method minimizes the sum of the squares of the differences within each group in order to form groups with the least possible variation between species within the same group, according to Equation (2):

$$W = \sum_{i=1}^n \sum_{j=1}^n d_{ij} \quad (2)$$

To determine the ideal number of clusters in this study, we used the Gap statistic, an effective technique that compares the dispersion of the real data within the clusters obtained with a null reference, which is a random uniform distribution of the data. Initially, we calculated the intra-cluster dispersion W_k for different values of k (number of clusters), which represents the sum of the squared distances within each cluster, providing a dispersion measure of the real data for each cluster configuration.

Thus, we generated several samples of random data uniformly distributed within the data space and calculated the intra-cluster dispersion W_k for the same k values. This process generates a null reference that allows us to compare the dispersion of the real data with the dispersion expected at random.

The gap statistic is then calculated as the difference between the logarithm of the average dispersion of the random data and the logarithm of the dispersion of the real data according to Equation (3):

$$Gap(k) = \frac{1}{B} \sum_{b=1}^B \log(W_k^*(b)) - \log(W_k) \quad (3)$$

where B is the number of random data samples. This metric helps us identify the optimal number of clusters k^* , which is the one that maximizes the gap statistic.

In other words, k^* is chosen where the difference between the dispersion of the real data and the dispersion of the random data is most significant, indicating distinct and relevant groups in the timber technological characteristics of the species analyzed. This statistical approach ensures that the definition of the clusters' number is not arbitrary but based on a rigorous mathematical foundation, guaranteeing that the groups identified accurately reflect the similarities and differences between the species evaluated.

After determining the optimal number of clusters, we used the `fviz_cluster` function from the `factoextra` package in R to visualize the clustering results. This function provides a powerful and intuitive way to plot the clusters in a two-dimensional space, where each species is represented as a point. The `fviz_cluster` function uses the results of a Principal Component Analysis (PCA) to reduce the dimensionality of the data, projecting it onto two

main axes—referred to as Dim 1 and Dim 2—which capture the maximum variance in the data. Dim 1 and 2 represent the two most significant components derived from the PCA, summarizing the overall variability in the species' technological characteristics.

Each cluster is displayed with a different color, making it easy to distinguish the groups visually.

The points (species) within the same cluster are grouped closely together, indicating that they share similar technological characteristics, while points in different clusters are spread further apart, reflecting their dissimilarities.

The `fviz_cluster` function also adds convex hulls around the clusters, further enhancing the visual separation between them. This visualization is crucial for interpreting the structure of the clusters, as it allows us to see how well the species are grouped according to their characteristics and whether the clusters are distinct from one another.

In addition to `fviz_cluster`, the `fviz_dend` function was employed to generate a dendrogram, which provides a hierarchical visualization of the clustering process, illustrating how species were progressively grouped based on their technological characteristics. These visualizations were essential for ensuring that the clusters formed were coherent and aligned with the economic potential and usage patterns of the species.

3. Results

The optimal statistical interval (k) obtained was approximately 0.57, resulting from the formation of four homogeneous groups among the most and least traded species (Figure 1). The separation of these species into four groups and the consequent formation of clusters was based on various attributes of these species. Among these attributes, however, wood basic density (kg m^{-3}) showed the greatest predominance and, consequently, had the greatest influence in separating these groups.

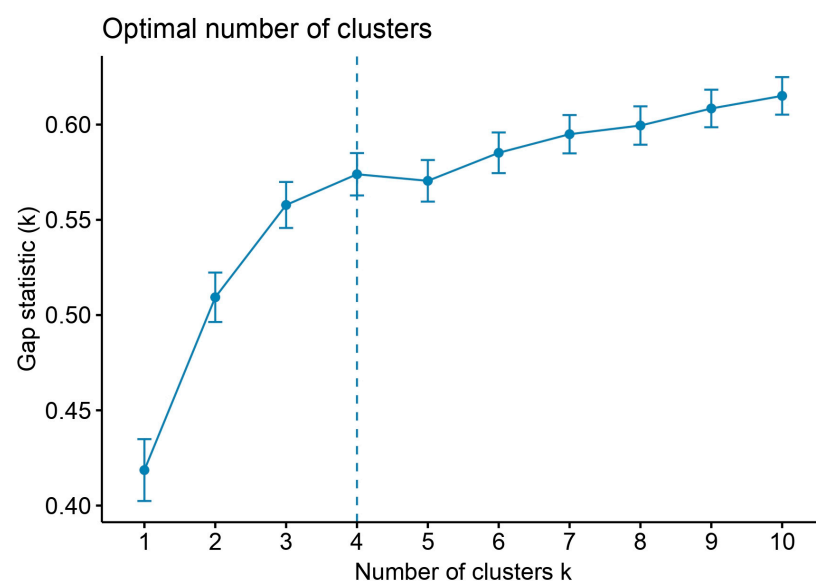


Figure 1. Sum of squares within the clusters to determine the optimal number of clusters.

As a result of the observation, 10.83% of the inventoried and assessed species were classified as more commercial, while 89.18% were classified as less commercial. The cluster analysis grouped 40.72% of the species (79 species) into Cluster 1, which predominantly includes species with low wood density ($<690 \text{ kg m}^{-3}$). Within this group, 11 species were considered more commercial, and 68 were seen as less commercial. Thus, this was the group with the highest number of species identified as potential alternatives to the 11 commercial species (Figure 2).

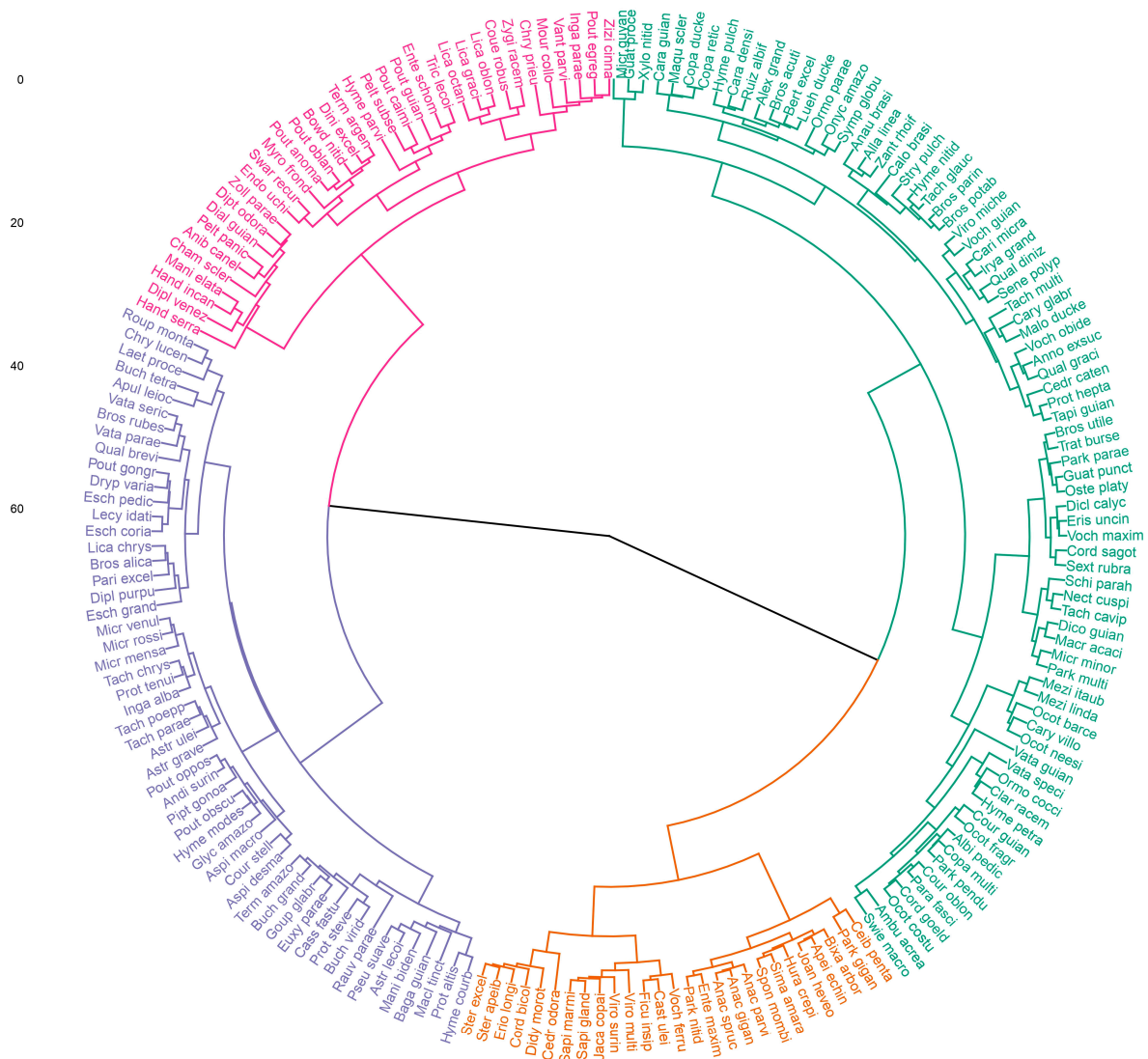


Figure 2. Dendrogram with the formation of the four clusters, with homogeneous groups of species, based on the technological characteristics of the wood.

Cluster 2, on the other hand, grouped 27 species (13.92% of all species), all of which were classified as less commercial. This means that these species did not fit into any of the other three groups with potentially alternative, more commercial species. The species in this cluster generally had a basic wood density between 260 and 520 kg m⁻³. Cluster 3 grouped 53 species (27.32% of the total) with a predominant wood density between 550 and 830 kg m⁻³, of which six were classified as more commercial and 47 as less commercial. Finally, Group 4 had 35 species (18.04%) with a predominant average wood density of 830 kg m⁻³, represented by four more commercial species and 31 less commercial species indicated as potential alternatives. The dendrogram in Figure 2 shows the four groupings.

Figure 3 describes the vector arrangement of the four clusters.

The data presented in Table 1 shows that the 20 most traded species, according to Timberflow (2023) and the forestry company and concessionaire Cemal, account for 43.66% of all the wood commercialized in the Amazonian forest. The three most traded species (*Dipteryx odorata*, *Manilkara huberi*, and *Dinizia excelsa*) have a basic wood density considered high (above 800 kg m⁻³).

As expected, the vast majority (70%) of the 20 species listed are classified as most commercial (MAC). Most of these species fall into Clusters 3 and 4, with basic density values ranging

from 750 to 910 kg m⁻³, being, therefore, high-density wood species. From the 20 species listed, those in Cluster 1 had lower basic density values, ranging from 460 to 630 kg m⁻³.

The species status regarding extinction threat, according to the IUCN (2024) Red List, showed that most of the 20 species (65%) are classified as “Least Concern”, which denotes such species present no extinction risk, apparently. Among the five most commercialized species, only *Manilkara elata* presented the “Endangered” status. On the other hand, the most commercialized species, *Dipteryx odorata*, does not present available data regarding the extinction threat status.

As for the abundance of the species, this variable does not show a very clear pattern in relation to the volume sold. The three most traded species had abundance values of less than 20 trees ha⁻¹, while the 4th (*Goupia glabra*), 13th (*Erismia uncinatum*), and 20th (*Peltogyne paniculata*) most exploited species had the highest abundances of 89, 50, and 50 trees ha⁻¹, respectively. This indicates that species abundance is a factor that is sometimes not considered in the exploitation and commercialization planning of Amazonian timberwoods. In these cases, the uses and commercial demand for such wood are predominantly considered instead.

Table 2 lists alternative species for each of the five most commercialized species in the Amazon, according to Timberflow, 2023. These alternative species were identified based on a cluster analysis that considered the physical-mechanical properties of the wood. For the species *Dipteryx odorata*, the alternatives are *Dialium guianense* and *Zollernia paraensis*. Both species present the status of “Least Concern”, and they also have basic densities (above 800 kg m⁻³) and physical-mechanical characteristics similar to *Dipteryx odorata*. *Dialium guianense*, with an abundance of 64 trees per hectare, has considerable availability, making it a good alternative. Additionally, this species’ timberwood presents a slightly similar color to the *Dipteryx odorata* timberwood color.



Figure 3. Vector arrangement of the species that make up the four clusters, based on the formation of the two axes. Dim1 and Dim2 refer to the first and second dimensions or the first and second principal components, respectively.

Table 1. List of the 20 most commercialized species (Timberflow, 2023), together with information on the commercial class, cluster, and abundance.

Species	Rank	Cluster	Class	Abundance	IUCN Status	Basic Density	Acumulated Volume	Volume Percentage	Wood Color
				N° Trees ha ^{−1}		kg m ^{−3}	m ³	%	
<i>Dipteryx odorata</i>	1	4	SMC	19	Data Deficient	910	1,663,957.44	3.37	
<i>Manilkara elata</i>	2	4	SMC	5	Endangered	870	1,644,969.22	3.34	
<i>Dinizia excelsa</i>	3	4	SMC	7	Least Concern	830	1,638,570.24	3.32	
<i>Goupia glabra</i>	4	3	SLC	89	Least Concern	710	1,579,236.6	3.20	
<i>Hymenaea courbaril</i>	5	3	SMC	14	Least Concern	760	1,571,206.3	3.19	
<i>Couratari guianensis</i>	6	1	SMC	2	Least Concern	520	1,313,608.18	2.66	
<i>Apuleia molaris</i>	7	3	SMC	11	Least Concern	750	1,084,419.78	2.20	
<i>Handroanthus serratifolius</i>	8	4	SMC	22	Endangered	890	1,075,939.56	2.18	
<i>Caryocar villosum</i>	9	1	SLC	5	Least Concern	630	997,216.24	2.02	
<i>Hymenolobium petraeum</i>	10	1	SMC	3	Least Concern	590	996,565.62	2.02	

Table 1. Cont.

Species	Rank	Cluster	Class	Abundance N° Trees ha ^{−1}	IUCN Status	Basic Density kg m ^{−3}	Acumulated Volume m ³	Volume Percentage %	Wood Color
<i>Schizolobium parahyba</i>	11	1	SMC	15	Least Concern	490	994,244.22	2.02	
<i>Astronium lecointei</i>	12	3	SMC	23	Least Concern	750	960,512.66	1.95	
<i>Erismia uncinatum</i>	13	1	SMC	50	Least Concern	460	935,097.78	1.90	
<i>Qualea paraensis</i>	14			45	Least Concern		933,338.22	1.89	
<i>Cariniana micrantha</i>	15	1	SMC	4	Data Deficient	580	832,118.82	1.69	
<i>Clarisia racemosa</i>	16	1	SLC	16	Least Concern	600	808,492.2	1.64	
<i>Cedrelinga cateniformis</i>	17	1	SLC	37	Least Concern	450	706,828.42	1.43	
<i>Hymenolobium excelsum</i>	18			4	Data Deficient	800–900	630,257.7	1.28	
<i>Allantoma lineata</i>	19	1	SLC	35	Data Deficient	600	588,936.64	1.19	
<i>Peltogyne paniculata</i>	20	4	SLC	50	Data Deficient	810	572,719.12	1.16	

SMC: Species most commercialized by Comércio Ecológico de Madeiras Ltd.a. (CEMAL); SLC: Species least commercialized by CEMAL. Traded volume data—Source: Timberflow, 2023. Basic wood density data—Sources: Forest Products Laboratory (LPF/SFB) (<https://lpf.florestal.gov.br/pt-br/>, accessed on 20 June 2024) and Tropical Timber (<http://www.tropicaltimber.info/pt-br/specie/mandioqueira-qualea-paraensis/#lower-content>, accessed on 20 June 2024).

Table 2. List of alternative species for each of the five most traded species (Timberflow, 2023), based on the cluster analysis.

Alternative Species	Rank	Abundance N° Trees ha ^{−1}	IUCN Status	Basic Density kg m ^{−3}	Wood Color
<i>Dipteryx odorata</i>					
<i>Dialium guianense</i>	110	64	Least Concern	865	
<i>Zollernia paraensis</i>	427	26	Least Concern	970	
<i>Manilkara elata</i>					
<i>Handroanthus incanus</i>	199	3	Vulnerable	820	
<i>Diploon venezuelana</i>	-	-	Data Deficient	850	
<i>Dinizia excelsa</i>					
<i>Terminalia argentea</i>	15	271	Least Concern	800	
<i>Bowdichia nitida</i>	22	7	Least Concern	775	
<i>Goupia glabra</i>					
<i>Euxylophora paraensis</i>	356	4	Endangered	685	
<i>Buchenavia grandis</i>	75	19	No Information	755	
<i>Terminalia amazonia</i>	27	33	Least Concern	800	
<i>Hymenaea courbaril</i>					
<i>Protium altissimum</i>	-	128	Least Concern	740	-
<i>Maclura tinctoria</i>	470	52	Least Concern	730	
<i>Bagassa guianensis</i>	45	5	Least Concern	700	
<i>Manilkara bidentata</i> subsp. <i>surinamensis</i>	-	-	Least Concern	830	
<i>Astronium lecointei</i>	12	23	Least Concern	770	
<i>Pseudopiptadenia</i> <i>suaveolens</i>	51	14	Least Concern	740	
<i>Rauvolfia paraensis</i>	-	2	No Information	550	

In the case of *Manilkara elata*, the species *Handroanthus incanus*, which has an abundance of three trees per hectare, and is classified as “Vulnerable” according to the IUCN (2024) Red List, may be a limited alternative due to its low availability. *Diploon venezuelana*, with no specific abundance data available, needs further investigation to confirm its viability as an alternative. Among the alternative species to *Dinizia excelsa*, *Terminalia argentea* stands

out for its high abundance (271 trees per hectare), a “Least Concern” extinction threat, and very similar basic wood density (800 kg m^{-3}), as well as other physical-mechanical characteristics, offering a viable and sustainable alternative. However, such species present a different timberwood color compared to *Dinizia excelsa* color, which makes necessary further investigation about the market aesthetic demands for this timberwood.

For *Goupia glabra*, among the alternatives, the species *Terminalia amazonia*, with 33 trees per hectare and a “Least Concern” extinction threat, is highlighted due to its moderate availability and similar wood basic densities (800 kg m^{-3}), despite having a lower abundance compared to the assessed commercial species. As alternative species for *Hymenaea courbaril*, we found *Protium altissimum*, with 128 trees per hectare, and *Maclura tinctoria*, with 52 trees per hectare, which are excellent alternatives due to their high availability and similarly high wood basic densities (740 and 730 kg m^{-3} , respectively). Additionally, both species present a “Least Concern” status, which reinforces their applicability as complementary species. The species *Manilkara bidentata* subsp. *surinamensis* and *Rauvolfia paraensis* require more data on abundance to confirm their viability.

Wood color plays a fundamental role in the market, directly influencing product demand and value. In this study, color was not a variable considered in the data analysis but has been included in the text for visualization purposes. For the five most commercially traded species (Table 1) and their alternatives (Table 2), the wood colors can be viewed on the public site of the Forest Products Laboratory [25].

4. Discussion

The results obtained have shown evidence of overexploitation of a highly restricted group of species. The Amazon region harbors a diverse array of species, each valued in distinct ways: some hold economic significance due to their high market value, particularly in luxury furniture; others are crucial for ecosystem health; and some are utilized by traditional communities for medicinal and artisanal purposes. International demand for these high-value woods directly influences their exploitation in Brazil, aligning it with consumer preferences. Such demand can drive unsustainable practices, complicating efforts to promote sustainable alternatives. Selective logging often prioritizes market demand over species abundance, thereby posing risks to conservation and the long-term sustainability of management practices [26–28].

According to the study performed by [24], 20 of 998 species analyzed and present in the market have been excessively exploited. The authors further state that approximately 52% of timber harvesting in the Amazon region, amounting to around 80 million cubic meters of wood (between 2007 and 2020), is concentrated on exploitation, leading to the depletion of 15 to 20 species.

Among the species most sought after during the survey, *Manilkara huberi* stands out, coming in 2nd place in the ranking of most exploited species, with an abundance of only three trees ha^{-1} . Species like this one, which are intensively exploited and have a low number of individuals per hectare, not only represent a potential risk of extinction but also make their long-term exploitation legally unfeasible, given the need to leave remnant trees. In the state of Pará, in the Brazilian Amazon, where this study was performed, current legislation stipulates that at least three trees of each species, or 10% of the trees per Annual Production Unit (UPA), be left per 100 hectares, which makes the exploitation of species with few individuals not viable.

Ferreira et al. 2020 [27] evaluated the behavior of *Manilkara huberi* when subjected to logging in a managed area in the Amazon, with an emphasis on the time necessary for its stock recovery after exploitation. The authors found that differentiated management practices that favor the survival of *Manilkara huberi* over the course of cycles are essential, highlighting the need to look for alternative species in future cycles to avoid negative impacts on the conservation of this species.

In addition to *Manilkara huberi*, well-known trees such as *Hymenaea courbaril*, *Handroanthus impetiginosus*, *Dipteryx odorata*, and *Cariniana legalis* are also on the list. The reason

they are the most exploited is not only related to the specific properties of these woods but especially to the interest of the consumer market [24]. This fact increases the risks of overexploitation of these groups, which highlights the importance of the search for alternative species that are able to meet the market demands, which would considerably relieve the pressure on stocks of these intensively logged species [11,28,29].

In analyzing the dynamics of tree species over 30 years of logging and thinning in a managed forest in the Amazon, it was found that intense exploitation and thinning led to a progressive reduction in the timber stocks of the exploited species. The authors emphasize the importance of directing extraction in subsequent cycles to species that have not yet been logged, aiming to ensure a sustainable balance in timber stocks over the long term, which supports the thesis presented in this study [30].

The 68 species in Cluster 1, together with the 78 species in Clusters 3 and 4, show that it is feasible to look for alternative species with different wood densities and for different uses in polycyclic management systems. Thus, it is important to observe that the feasibility of establishing a list of alternative species from intensively exploited groups must include not only a survey of similar characteristics between species but also the phytosociological behavior of these species, especially in response to disturbances caused by exploitation throughout the cutting cycles [30,31].

In this regard, studies such as [31] highlight the possibility of mapping potentially alternative species from overexploited groups. The authors assessed the effects of over 30 years of exploitation on the structure and composition of the *Laetia procera* (Poepp.) population in a managed area in the Eastern Amazon, finding that this species has the potential to be used as an alternative to intensively exploited species.

A more specific analysis of alternatives to the five most traded species in the Amazon (Table 2) shows that there are several species with similar physical and mechanical characteristics that can be exploited sustainably, helping to relieve pressure on intensively exploited species. The main species identified as alternatives to the five most exploited species (Timberflow, 2023) have a high basic wood density (above 700 kg m^{-3}) and other physical-mechanical characteristics that turn them viable management options [12].

However, the abundance of these species varies considerably, which must be considered when planning exploitation and marketing programs [12,28]. Species with high abundances, such as *Terminalia argentea* and *Protium altissimum*, are more suitable as viable alternatives. These species, in addition to having high-density wood and other characteristics similar to their intensively exploited representatives (*Dinizia excelsa* and *Hymenaea courbaril*, respectively), because their higher individual density, can be less disturbed by exploitation practices in subsequent cycles, which makes them extremely promising. Obviously, other phytosociological characteristics must be evaluated to corroborate the high resilience these species can present, so that it is possible to include them in management programs as alternatives [26,32].

On the other hand, species identified as potential alternatives but with lower abundance require careful evaluation to ensure the sustainability of their exploitation, especially in polycyclic management programs. This caution is necessary to prevent these species from suffering overexploitation and depletion in the forest, as observed with the overexploited species addressed in this study.

5. Conclusions

This study demonstrates that the cluster analysis was effective in forming four homogeneous groups of Amazonian timber species, primarily based on wood basic density. This approach identified seven species as potential alternatives to the five most commercialized ones, crucial for mitigating the overexploitation of a narrow group of dominant species in the timber market. Species abundance does not follow a clear pattern regarding commercial volume, indicating that the market demand may not consider natural species availability. This approach emphasizes the importance of considering not only the technological properties of woods but also their phytosociological behavior to ensure the

ecological and economic viability of proposed alternatives. Accepting alternative species makes it feasible for the market to support at least the second cycle of production in forest concession projects.

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