

Article

Topoclimatic Zoning of Three Native Amazonian Forest Species: Approach to Sustainable Silviculture

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Abstract: Anthropized areas in the Brazilian Amazon require detailed mapping to identify zones for sustainable use. This study developed a topoclimatic zoning framework to evaluate the conservation and agroforestry potential of three native species: *Carapa guianensis* (Andiroba), *Dipteryx odorata* (Cumaru), and *Bertholletia excelsa* (Amazon Nut). The hypothesis was that integrating topographic and climatic data can effectively identify high-potential areas for these species to support forest restoration and sustainable management. This study applied ecological modeling and Geographic Information System (GIS) tools to classify zones into high, medium, and low potential for each species. Results showed *Carapa guianensis* has high potential in 64% of anthropized areas, *Dipteryx odorata* in 72% of the Legal Amazon, and *Bertholletia excelsa* in 58%, highlighting their adaptability and strategic value for restoration efforts. The findings emphasize the importance of topoclimatic zoning as a tool for conservation and sustainable use strategies. By aligning with Brazil's Payment for Environmental Services (PES) Law, this approach can foster agroforestry practices, enhance biodiversity conservation, and strengthen the Amazon bioeconomy, ensuring ecological resilience and sustainable development.

Keywords: conservation; environmental recovery; land use; geoprocessing; sustainability



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1. Introduction

Ecosystem dynamics are shaped by interactions between abiotic factors and organisms, with climate as a key regulator. Phenological responses are influenced by specific environmental conditions [1], driven by genotype-environment interactions. Topographic factors (elevation, slope) and climate interact to create microclimates affecting species growth.

Topographic factors, such as elevation and slope, are key variables that, when combined with climatic conditions, create microclimates that significantly affect plant growth and development. For instance, variations in temperature, rainfall, air and soil moisture availability, and sunlight exposure across different topographic gradients shape the phenological patterns of species. These ecological interactions are essential for the successful establishment, growth, and reproduction of plant species within a given habitat [2,3].

Understanding the interactions between climatic and topographic variables provides critical insights into species distribution and ecosystem dynamics. This knowledge also informs conservation strategies, forest management, and sustainable agricultural practices, particularly in regions vulnerable to climate change. By integrating ecological, climatic, and topographic data, researchers can more accurately predict phenological changes and their implications for biodiversity and ecosystem services [4].

Climatic variables such as air temperature, annual and monthly rainfall totals, as well as soil water stocks, among others, are capable of explaining certain occurrences of plant species in a given location or region [5]. In fact, rainfall, due to its variability, can influence the biogeography of many species that are more sensitive to soil water stocks. There are species that occur in a wide rainfall range, such as *Schizolobium amazonicum*, which can occur in a wide rainfall range.

When introducing this forest species for enrichment in canopy gaps using *Schizolobium parahyba* var. *amazonicum* (Huber ex Ducke) seeds in [6], the authors observed that it is highly suitable for post-harvest silvicultural recovery strategies. Over a period of 13 years (1995–2008), the species demonstrated an impressive growth rate, increasing by $3.1 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ in tree volume for individuals with a diameter at breast height (DBH) exceeding 25 cm. Furthermore, more than 30% of the planted seeds successfully reached a DBH greater than 25 cm, indicating rapid growth and strong potential for use in forest restoration initiatives.

How can deforested areas, which were cleared under public policies promoting regional development and integration with other parts of the country, be restored? Hallmarks of this era include the construction of the Belém-Brasília and Trans-Amazonian highways. Another significant factor worth reflecting upon is the expeditions of the RADAMBRASIL Project. Adopting a methodological approach that integrates data on abiotic variables and the distribution of high-value forest species could significantly enhance strategic planning for forest restoration in the regions degraded areas. This strategy would provide a science-based foundation for identifying priority areas, optimizing restoration efforts, and promoting the recovery of ecological and economic value within these landscapes. This approach could provide a scientific basis for developing targeted and sustainable restoration efforts [7].

Discussions on socio-ecological governance in the Brazilian Amazon and other tropical regions increasingly highlight the need for integrated approaches to control deforestation. These approaches involve the active participation of multiple stakeholders, including public, private, and civil society sectors, to develop innovative solutions for reducing deforestation [8]. Furthermore, they emphasize the importance of identifying restoration strategies that utilize native forest species to support ecological recovery in the region. Analyses of landscape patterns in the Brazilian Amazon indicate that forest loss not only intensifies global warming but also significantly reduces evapotranspiration, with decreases of up to 34% during the dry season [9].

Areas that still contain native forests require greater attention, particularly regarding the ecosystem services they provide, such as provisioning, regulation, support, and cultural benefits [10]. Estimates of Amazonian biodiversity suggest a species richness ranging

from approximately 7000 [11] to 16,000 species [12,13], many of which are threatened by anthropogenic processes, especially the expansion of deforestation.

The use of ecological variables is crucial for understanding and managing ecosystem dynamics, as evidenced in the study in [14]. The study highlights the integration of these variables in forecasting models, emphasizing their role in predicting bloom persistence, magnitude, and shifts. Such applications demonstrate the broader importance of ecological variables in developing adaptive management strategies, mitigating ecosystem risks, and addressing global challenges such as climate change and biodiversity loss.

The integration of ecological variables into decision-making frameworks has proven essential for addressing complex challenges in both aquatic and terrestrial ecosystems. Just as chlorophyll-a (CHL-a) serves as a systemic eco-indicator for managing algal blooms and their cascading impacts, the identification of knowledge gaps in the silviculture of native forest species in Brazil underscores the need for a similar approach in forestry. Research and Development (R&D) programs targeting 30 native tree species—15 from the Amazon and 15 from the Atlantic Forest biomes—highlight the importance of understanding species-specific requirements and site conditions [15]. This strategy can enhance the success of reforestation initiatives, supporting the restoration of 12 million hectares of degraded land and fostering the sustainable development of timber and non-timber product markets, as exemplified by programs in Rondônia [16]. By bridging these approaches, both aquatic and terrestrial systems benefit from science-driven strategies that address ecological complexity and promote resilience.

Topoclimatic zoning (TopZon) emerges as a pivotal tool for decision-making in reforestation and silviculture, integrating topographic and climatic variables to identify areas with high, medium, and low potential for planting. By guiding the selection of optimal locations, TopZon helps maximize the success of forest plantations while mitigating risks associated with adverse environmental conditions. This methodology, akin to predictive models used in other ecological contexts, provides strategic insights for restoring degraded landscapes and fostering sustainable forestry practices. Studies [17–19] have consistently demonstrated the effectiveness of TopZon in pinpointing suitable areas for planting native species and supporting the development of robust silviculture strategies.

Among the native species with high potential for strengthening bioeconomic production chains in the Legal Amazon is *Carapa guianensis*, commonly known as Andiroba. This species naturally occurs in a range of environments, including lowland areas, riverbanks, streams, and dryland areas, but its survival critically depends on the availability of abundant water [20]. Andiroba offers multiple uses, serving both as a timber resource [21] and as a source of valuable non-timber forest products (NTFPs), such as oils used in natural medicine [22,23] and other by-products [24,25]. The strategic application of topoclimatic zoning (TopZon) can significantly enhance the successful cultivation of Andiroba by identifying optimal planting locations based on its ecological requirements.

Another tree species with significant bioeconomic potential is *Dipteryx odorata*, commonly known as Cumaru. This species occurs naturally in dryland rainforests [26] and can grow up to 30 m tall in primary forests, although it is typically smaller when cultivated or present in secondary forests [27,28]. Long-lived forest species require many generations—potentially spanning over 300 years—to exhibit significant genetic changes. The extent and rate of impacts caused by its exploitation depend heavily on the size of the harvested area and the presence of external gene flow in the regions where the species occurs [29].

Cumaru has multiple uses, including the commercialization of its highly valued and durable wood [30,31], as well as the trade of its seeds, which hold substantial commercial value due to their rich coumarin content. This compound is widely used in perfumery, phar-

maceuticals, and flavoring industries, enhancing the species' economic significance [32]. This highlights the critical importance of genetic conservation strategies for Cumaru, ensuring the maintenance of its genetic diversity and resilience against environmental and anthropogenic pressures. This approach not only supports the sustainable use of Cumaru's resources but also contributes to preserving the ecological balance of Amazonian ecosystems, promoting bioeconomic development and long-term environmental sustainability.

The Amazon Nut (*Bertholletia excelsa*) also deserves special attention as a key species of the Amazon biome. Its fruits contain almonds of high nutritional and energy value, widely utilized in human diets [33]. The species is easily recognizable within the Amazon rainforest canopy [34,35], where it plays critical ecological roles and contributes significantly to ecosystem services, such as carbon storage, nutrient cycling, and supporting biodiversity [36,37]. By identifying areas with optimal environmental conditions for its growth, such as appropriate soil types, water availability, and climate characteristics, we can guide reforestation and plantation efforts.

The hypothesis is that the integration of topographical and climatic variables can identify preferential areas for the cultivation of these three native Amazonian species. By incorporating biophysical variables, agrometeorology, multivariate statistics, and Geographic Information Systems (GIS) tools, the approach aims to classify areas into high, medium, and low potential zones for each species analyzed. The objective of this study was to develop topoclimatic zoning as a strategic tool for the sustainable management of three native Amazonian forest species.

2. Materials and Methods

The Legal Amazon, established by Law 5173 of 27 October 1966, covers approximately 60% of the Brazilian territory. The Federative Units that make up the Region are Acre, Amapá, Amazonas, Pará, Mato Grosso, Rondônia, Roraima, and Tocantins, and part of the State of Maranhão west of the 44° W meridian. The region was delimited with a view to defining public policies capable of promoting the economic development of the region, which, according to [38], the diagnosis at that time considered that the region had a demographic void. Thus, measures were taken that caused inversions of values, since the forest has an important role in maintaining biodiversity and, consequently, its effects on regulating the global climate [39–41].

The Topoclimatic Zoning (TopZon) methodology for native Amazonian species was developed and tested, first for two native Amazonian species [18] and tested using validation methods, including field validations in [42]. It is worth noting that the methodological synthesis was presented in [19]. However, it is explained that TopZon assumes that the distribution and abundance of species respond to climatic and relief factors, where variables such as temperature, precipitation, exposure to solar radiation levels, and air humidity, among other variables, can signal certain habitats on the globe [43,44].

The spatial data collected during the RADAMBRASIL Project represent one of the most comprehensive evaluations of timber potential ever conducted in the Amazon. These inventories, carried out in the 1970s and 1980s, were initiated during a period when the region was still perceived as a demographic void [45]. The primary goal of these surveys was to identify native species with significant timber potential within the boundaries of the Legal Amazon, a region formally defined by Decree-Law No. 291 on February 28, 1966 [38,46]. The Brazilian Institute of Geography and Statistics (IBGE) now provides access to this valuable dataset through its Environmental Information Database (BDiA), ensuring that the historical occurrence records of native species are readily available. These records form the foundational dataset for developing models aimed at understanding species distribution and supporting sustainable resource management in the region.

Occurrence data included the Global Biodiversity Information Facility (GBIF, www.gbif.org), herbarium databases, and bibliographic reference repositories with inventory records. These supplementary datasets were integral to validating the topoclimatic zoning (TopZon) model for each species analyzed in this study, specifically *Carapa guianensis*, *Dipteryx odorata*, and *Bertholletia excelsa*. Following the spatial modeling process, a comprehensive analysis assessed whether areas identified as having high, medium, or low potential in the TopZon model aligned with actual occurrence points obtained from these external databases. This validation step was essential for evaluating the model's accuracy and ensuring its reliability in guiding sustainable management strategies.

The climate variables used came from a daily gridded dataset, available in NetCDF (Network Common Data Form) format, at a spatial resolution of $0.1^\circ \times 0.1^\circ$, totaling 41,115 virtual stations throughout the study area. This information is called Brazilian Daily Weather Gridded Data (BR-DWGD) [47]. The climate variables used were precipitation, minimum, maximum, and average temperature, solar radiation (RS, $\text{MJ m}^{-2} \text{ day}^{-1}$), wind speed at 2 m height (u_2 , m s^{-2}), potential evapotranspiration (ETP, mm), and relative humidity (RH, %), with all these variables referring to the period from 1961 to 2022, from the database made available in [47,48].

The research in [49] analyzed the performance of BR-DWGD in relation to AgCFSR and AgMERRA and NASA/POWER [50]. They found that BR-DWGD had better statistical performance when compared to the observed data. Similar results were also found in [51–53].

The climate typology map was prepared using the historical series between 1961 and 2022 [47], applying the [54], which is the most widely used classification worldwide [55], but using the adaptation proposed in [56]. Because the historical series includes data estimated for 61 years, the average was calculated, obtaining different results from those obtained in [17–19], precisely because the database was a 30-year climatological normal.

In this study, the climate typology map was developed using the Köppen methodology, as adapted in [56]. Unlike the previous map used in [19], which relied on grid data with a resolution of $1^\circ \times 1^\circ$, this analysis utilizes a new historical dataset (1961–2022) with significantly enhanced spatial detail. The improved resolution of $0.1^\circ \times 0.1^\circ$ provides a much more accurate representation of climate patterns, allowing for a more detailed and precise analysis of climate typology. This advancement ensures a better spatial characterization, which is crucial for more reliable applications and interpretations.

To conduct this analysis, information layers were generated for each climate variable using the available data. These variables include total annual rainfall (TAR, mm), total rainfall in the least rainy quarter (TLRQ, mm), total rainfall in months with <100 mm ($\text{RF} < 100$ mm), and total rainfall in months with <60 mm ($\text{RF} < 60$ mm). Additionally, temperature metrics were considered, such as maximum temperature (TM_x , $^\circ\text{C}$), average temperature (TAvg , $^\circ\text{C}$), and minimum temperature (TMin , $^\circ\text{C}$). Other atmospheric parameters included relative humidity (RH, %), vapor pressure deficit (VPD, kPa), and variables derived from the climatological water balance.

Moreover, topographic (altitude) and geographic (longitude and latitude) data were incorporated into the analysis. These variables are essential for understanding the distribution of species, as they provide insights into the adaptive capacity of species to the climatic conditions of their natural habitats. By integrating these diverse datasets, this study aims to capture the multifaceted environmental factors influencing species distribution and resilience.

The vapor pressure deficit (VPD) is a climatic variable derived from other parameters, serving as an indicator of potential water stress conditions in plants. High VPD values are

associated with increased water loss through leaves, which can lead to stomatal closure and a consequent reduction in photosynthetic activity [56].

The determination of the climatological water balance (BH) was also included in the analysis: real evapotranspiration (ETP, mm), water stress (WST), and water surplus (WSP, mm), followed the methodology of [57] using a soil available water capacity (AWC) of 300 mm, considering that the analysis is focused on forest species plantations [3,58]. The potential evapotranspiration calculated on the BR-DWGD platform, estimating the following components of the BHC, according to the logical sequence contained presented in [14].

Another variable included in the database is the standardized precipitation index (SPI), which indicates the intensity and occurrence of dry periods in relation to wet periods [59]. Therefore, for each of the 41,115 points, the SPI was calculated to normalize the variability of precipitation over the 61 years of data throughout the Legal Amazon, allowing for consistent and more robust comparisons. Unlike deviations from the average precipitation, which can vary significantly between regions, the SPI provides normalized data that can be universally applicable [60].

The gamma probability density function [61] is used to calculate the SPI. Therefore, the precipitation data were adjusted to the gamma distribution to evaluate the variability of rainfall in the region. The gamma distribution parameters were estimated for each point in the $0.1^\circ \times 0.1^\circ$ grid and for each month of the year. The SPI is obtained using the observed precipitation value, subtracting it from the mean of the studied period, and dividing it by the standard deviation [59].

The index can be used to monitor drought events at local, regional, and large-area levels [62]. The accuracy of the index decreases as time scales increase, and scales greater than 24 months are not recommended. Furthermore, care must be taken with the sample size, which must be representative [63]. In addition, smaller scales are associated with soil moisture, and larger scales are related to scarcity of water resources such as rivers, lakes, and groundwater. Standardization is necessary to allow indices calculated under different climatic conditions to be compared with each other [63]. Another important point is that arid regions where zero values are common cause precipitation to be non-normally distributed, which can reduce the reliability of the SPI calculation [64,65]. SPI values can be classified according to Table 1.

Table 1. Standardized precipitation index (SPI) ranges and corresponding classes by SPI ranges adapted [60].

SPI Bands	Classes
≥ 2.00	Extremely Humid
1.50 to 1.99	Severely Wet
1.00 to 1.49	Moderately Humid
0.00 to 0.99	Incipient Dampness
0.01 to -0.99	Incipient Drought
-1.00 to -1.49	Moderately Dry
-1.50 to -1.99	Severely Dry
≤ -2.00	Extremely Dry

2.1. Statistical Analysis

A multiple linear regression model was applied to data from the entire Amazon region. To do this, we began by identifying a more appropriate dependent variable. In this sense, non-hierarchical cluster analysis using the K-means method was used to obtain the variable “Frequency” based on the classification of the groups formed. This method was chosen due to the large number of observations present in the data set.

After defining the dependent variable, stepwise variable selection methods (progressive and regressive) were applied to identify the most relevant variables for the regression model [66]. The final model was chosen based on the Akaike Information Criterion (AIC), selecting the model that presented the lowest value. After the selected model was chosen, the multiple linear regression analysis continued, considering the means of the independent variables according to the groups formed by the cluster analysis. The independent variables used are listed as follows: longitude, latitude, water stress (WST), RF < 100 mm, RF < 60 mm, TRA, RH, SPI, TMx, TAv, TMin, TLRQ, VPD, and altitude.

2.2. K-Means Cluster Analysis

Cluster analysis was performed using the K-means method, a non-hierarchical algorithm that divides a dataset into K groups by minimizing the sum of squares of the distances between observations and group centers [67,68].

Cluster analysis is a powerful tool that can significantly enhance zoning efforts by integrating variables associated with species occurrences, climatic conditions, and altimetry data. The primary goal of cluster analysis is to identify groups (species) of observations that are internally similar within a group and distinct from observations in other groups, based on a multivariate distance matrix. In this research, the pursuit of homogenous observations is essential for understanding which response variables exhibit similarity among groups.

Simultaneously, identifying heterogeneous observations provides insights into divergent groups and the specific variables driving these differences. This dual approach not only aids in classifying species and their associated environmental conditions but also deepens our understanding of the ecological and climatic factors shaping their distributions. For the analysis, the variables were standardized to present a mean of 0 and a unitary standard deviation. For each of the native Amazon forest species—Andiroba (*Carapa guianensis*), Cumaru (*Dipteryx odorata*), and Castanha-da-Amazônia (*Bertholletia excelsa*)—the coefficients of the variables in the models indicate how each environmental factor influences the growth or presence of these species.

Cluster analysis was adopted as a strategy to obtain the dependent variable, or response, to be used in the regression model. The silhouette plot was used to assess the quality of clusters in the data set. This technique provides a quantitative measure of the internal coherence of the established clusters. Different numbers of clusters were tested, with 18 clusters being selected as sufficient to obtain a good classification and, consequently, a good fit of the model. By analyzing the silhouette graph, it is possible to assess the quality of the separation between the groups.

Each point on the graph represents an object and its silhouette, which ranges from −1 to 1 [69]. Values close to 1 indicate that the objects are well grouped, that is, the average distance between an object and all others in the same group is smaller than the average distance between the same object and all objects in the closest group. Values close to 0 indicate that the object is on the border between two groups. Negative values suggest that the objects may be misclassified, as they are closer to a different group than to their own group [70,71].

Therefore, in the present work, this statistical analysis was adopted because it involves multiple pieces of information for the species where the information is more grouped, as shown in Figure 1. In all cases, both through the analysis of the silhouette graphs and the graphs containing the groups generated by K-means, it is possible to perceive the separation of the groups for each species analyzed.

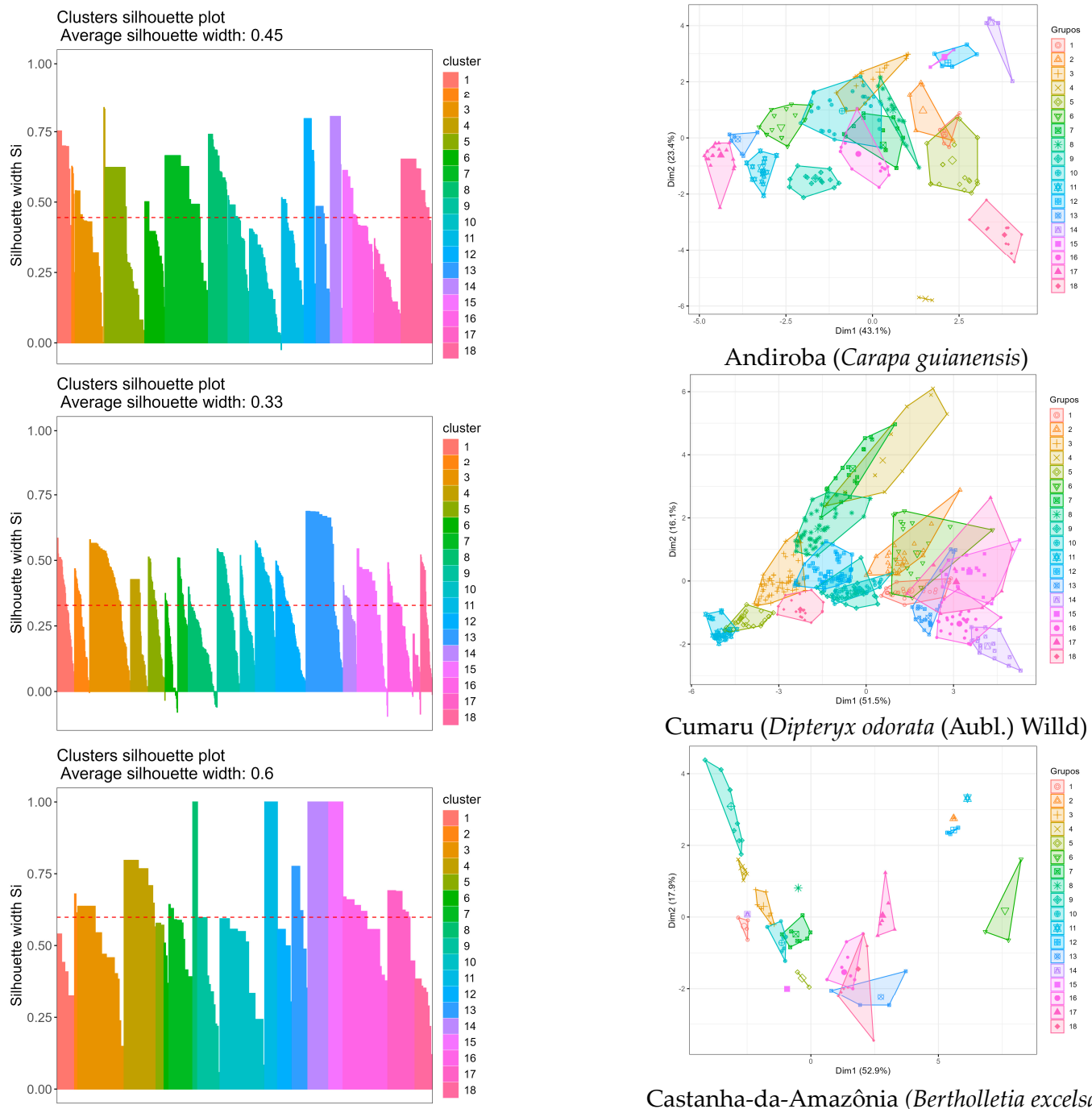


Figure 1. Evaluation of groups generated by silhouette analysis and K-means algorithm.

In Figure 2A–C, the residual graphs are presented, aiming to explain the adequacy of the regression model used, indicating that the positive residuals express that the observed values are higher than those predicted, while the negative residuals indicate the opposite. It is worth noting that the horizontal axis represents the theoretical quantiles, which are the expected values of a specific distribution, often the normal distribution. The black dots represent the sample residuals. The dotted line on the graph indicates a general trend of the residuals in relation to the theoretical quantiles. If the residuals followed a normal distribution, the points would be expected to be randomly distributed around the central line. The solid lines above and below the dotted line represent the confidence intervals for the residuals. If the points occur within these intervals, this suggests that the model is adequate, that is, that the model adequately describes the variability of the data.

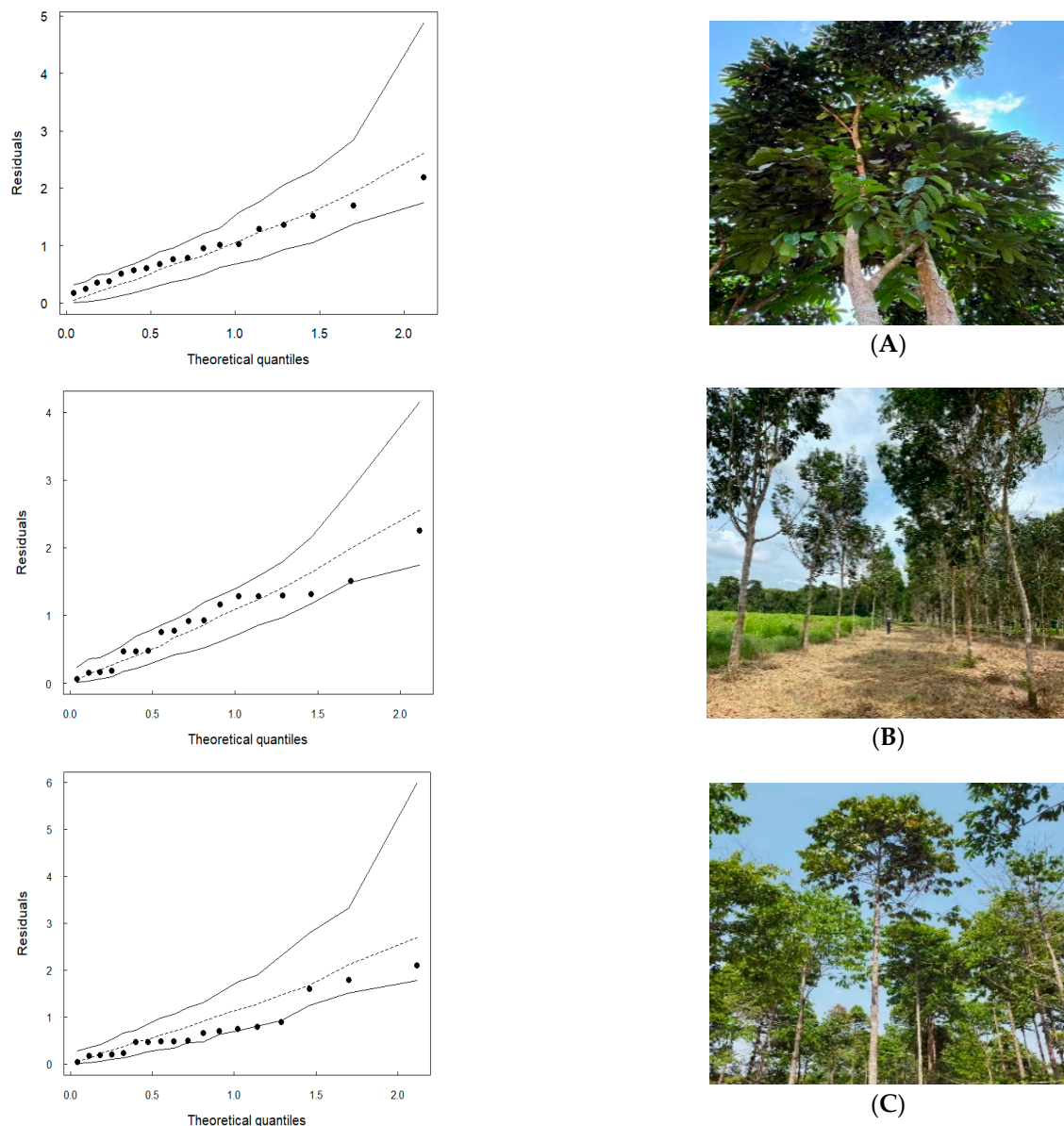


Figure 2. Distribution of sample residues when compared with theoretical quantiles for (A) Andiroba (*Carapa guianensis*), (B) Cumaru (*Dipteryx odorata* (Aubl.) Willd), and (C) Castanha-da-Amazônia (*Bertholletia excelsa* HBK).

2.3. Multiple Linear Regression

Multiple linear regression was used to model the relationship between the continuous dependent variable and several independent variables selected based on cluster analysis. This method allows the estimation of the combined impact of several explanatory variables between a continuous dependent variable and two or more independent variables [72]. The database also contains occurrence points for these 3 species, based on information available in herbaria and in the literature, with 1635 records for Andiroba (*C. guianensis*); 1081 for the Amazon Chestnut (*B. excelsa*); and 1251 for the Cumaru (*D. odorata*), with this occurrence information being used in the validation of the TopZon model for each species.

The mathematical framework for developing the topoclimatic zoning of the three native species studied across the entire Legal Amazon is structured based on Equations (1)–(3). These equations integrate key environmental variables to model the spatial distribution and ecological suitability of each species, as follows.

$$\text{Carapa guianensis} = 1106.7204 - 0.2393 \times (-0.3081) \times \text{RF} < 100 - 0.0154 \times \text{TRA} - 11.7748 \times \text{RH} - 233.8086 \text{SPI} - 0.0604 \times \text{TLRQ} + 97.4627 \text{VPD} - 0.1172 \times \text{altitude} \quad (1)$$

$$\text{Dipteryx odorata} = -1737.6914 - 11.5298 \times \text{latitude} + 0.6916 \times (-1.4859) \times \text{RF} < 60 - 188.2476 \times \text{SPI} - 26.7725 \times \text{TMx} + 94.2739 \times \text{TAvg} + 149.6787 \times \text{VPD} + 0.1912 \times \text{altitude} \quad (2)$$

$$\text{Bertholletia excelsa} = 1019.1649 + 7.3995 \times \text{longitude} - 1.7212 \times (-1.0354) \times \text{RF} < 100 - 1.1246 \times \text{RF} < 60 - 0.1093 \times \text{TAR} + 7.5324 \times \text{RH} - 93.0594 \times \text{SPI} - 20.7814 \times \text{TAvg} - 0.6269 \times \text{TLRQ} + 146.6152 \times \text{VPD} + 0.0586 \times \text{altitude} \quad (3)$$

Table 2 presents the adjusted models for each species, including the coefficients of the independent variables.

Table 2. Models with estimated coefficients for variables according to species.

Variable	Coefficient		
	Andiroba <i>Carapa guianensis</i>	Cumaru <i>Dipteryx odoratthe</i>	Castanha-da-Amazônia <i>Bertholletia excelsa</i>
Intercept	1106.72	−1737.69	1019.16
latitude	-	−11.53	-
longitude	-	-	7.40
WST	−0.24	0.69	−1.72
RF < 100	−0.31	-	−1.04
RF < 60	-	−1.49	−1.12
TLRQ	−0.06	-	−0.63
TRA	−0.02	-	−0.11
HR	−11.77	-	7.53
SPI	−233.81	−188.25	−93.06
VPD	97.46	149.68	146.62
TMx	-	−26.77	-
TAvg.	-	94.27	−20.78
altitude	−0.12	0.19	0.06

For Andiroba (*C. guianensis*), it is observed that the positive intercept (1106.72) suggests a high base for the response variable related to the presence or growth of *C. guianensis*. The negative WST (−0.24) indicates that under conditions of greater water deficit, there is a negative effect on the potential expression of Andiroba, reinforcing that the species depends on water availability for expression in growth and development. RF < 100 (−0.31) and TRA (−0.02) reinforce that the total precipitation with months above 100 mm and the annual precipitation have a negative influence, that is, there are water thresholds to guarantee the potential expression of this species. The RH (−11.77) indicates that high air humidity can harm the growth of Andiroba.

The SPI (−233.81) reinforces that the standardized precipitation index (SPI) with a negative value suggests that prolonged periods of above-normal rainfall are harmful, while the deficit is also not beneficial. TLRQ (−0.06): Accumulated precipitation in three months with less rainfall reinforces that Andiroba responds to balanced humidity conditions, but without excessive rainfall in short periods. The VPD (97.46): The vapor pressure deficit has a positive coefficient, suggesting that the species requires periods with greater evapotranspiration demand to favor the growth of Andiroba. However, Altitude (−0.12) indicates greater adaptability of the species at lower altitudes, typical of flooded areas or high floodplains.

Cumaru (*D. odorata*), the negative intercept (−1737.69) suggests that the model basis for Cumaru is unfavorable, with the negative coefficient for latitude (−11.53) suggesting that this species prefers to occur in lower latitudes, close to the Equator, where climatic

conditions present less variability. The WD (0.69) responds positively, evidenced that it is a species adapted to periods of moderate drought. In terms of RF < 60 (−1.49), it reinforces that months with rainfall totals below 60 mm have a negative effect, indicating that short periods of rain can be harmful, possibly because this is a species that has a high potential to drain photoassimilates to the almonds.

The SPI (−18.25) confirms that a negative coefficient reinforces greater tolerance to drought. In terms of Tmax (−26.77) and Tavg (94.27), it indicates that high temperatures are unfavorable, while moderate average temperatures are beneficial to Cumaru. The VPD (149.68), being positive, confirms that Cumaru prefers drier environments with greater evapotranspiration demand. The altitude (0.19) variable expresses greater adaptation of Cumaru to dry land areas in the Amazon rainforest.

For the Amazon chestnut (*B. excelsa*), the intercept (1019.16) is positive, reinforcing the adaptive capacity of this species to the Amazon environment. The positive coefficient for longitude (7.40) indicates that the Amazon chestnut (*Bertholletia excelsa*) is more likely to be found in areas further west within the Amazon region, suggesting a preference for locations with increasing longitudinal values. The WST (−1.72) confirms the sensitivity of the species to water deficit. Analyzing the model coefficients for RF < 100 (−1.04) and RF < 60 (−1.12) confirms the sensitivity to total rainfall values below 100 mm and 60 mm. TRA (−0.11) also confirms that this species responds negatively to total annual rainfall.

Analyzing the RH (7.53) shows that air humidity favors the presence of chestnut trees in typical environments of the Amazon rainforest. The SPI (−93.06) suggests that chestnut trees prefer areas with more stable conditions in terms of rainfall. The Tavg (−20.78) with this negative coefficient confirms that this is a species adapted to climatic conditions within the climatic patterns in the areas where it occurs. In the less rainy quarter, TLRQ (−0.63) in years with reduced accumulated rainfall in three months negatively affects the potential expression of this species. Observing the positive VDP (146.62) indicates that the best locations are preferably environments with high evapotranspiration demand, but with maintenance of water stocks in the soil. In terms of altimetry, altitude (0.06) suggests a slight preference for areas of low to medium altitude.

3. Results and Discussion

The approach was based on the classic [53], the most widely used globally for categorizing climates, as pointed out in [54]. For the Legal Amazon, the adaptation proposed in [55] was adopted based on the historical series that consists of 61 years of data, covering the period from 1961 to 2022, using the last two years following the base period established in [73], but based on the data available on the website.

In Figure 3 the climate pattern is presented to support strategic planning, especially when it comes to integrated analyses of the soil–plant–atmosphere system, as indications of areas cultivated with agricultural and/or forestry species. It is possible to identify that the occurrence ranges of each climate subtype have typical Af₁ conditions (3.3%) in areas with precipitation greater than 3000 mm per year. These areas are concentrated mainly in regions close to the state of Amazonas and some areas of Amapá. This high rainfall index is associated with high humidity and the presence of dense forest, crucial for the maintenance of local ecosystems.

In the Af₂ subtype (8.5%), rainfall amounts vary in terms of annual average between 3000 and 2500 mm. This subtype covers a significant portion of the Amazon, encompassing areas where the tropical forest adapts to high humidity, but with a slight reduction in relation to Af₁. This climate is still essentially humid, supporting lush forests and high biodiversity. In the Af₃ subtype (16.0%), annual rainfall is concentrated between 2500 and 2000 mm, distributed across several areas, especially in the south of Amazonas and west

of Pará. Humidity is still high, allowing the presence of tropical forests, although greater climate variability is already observed.

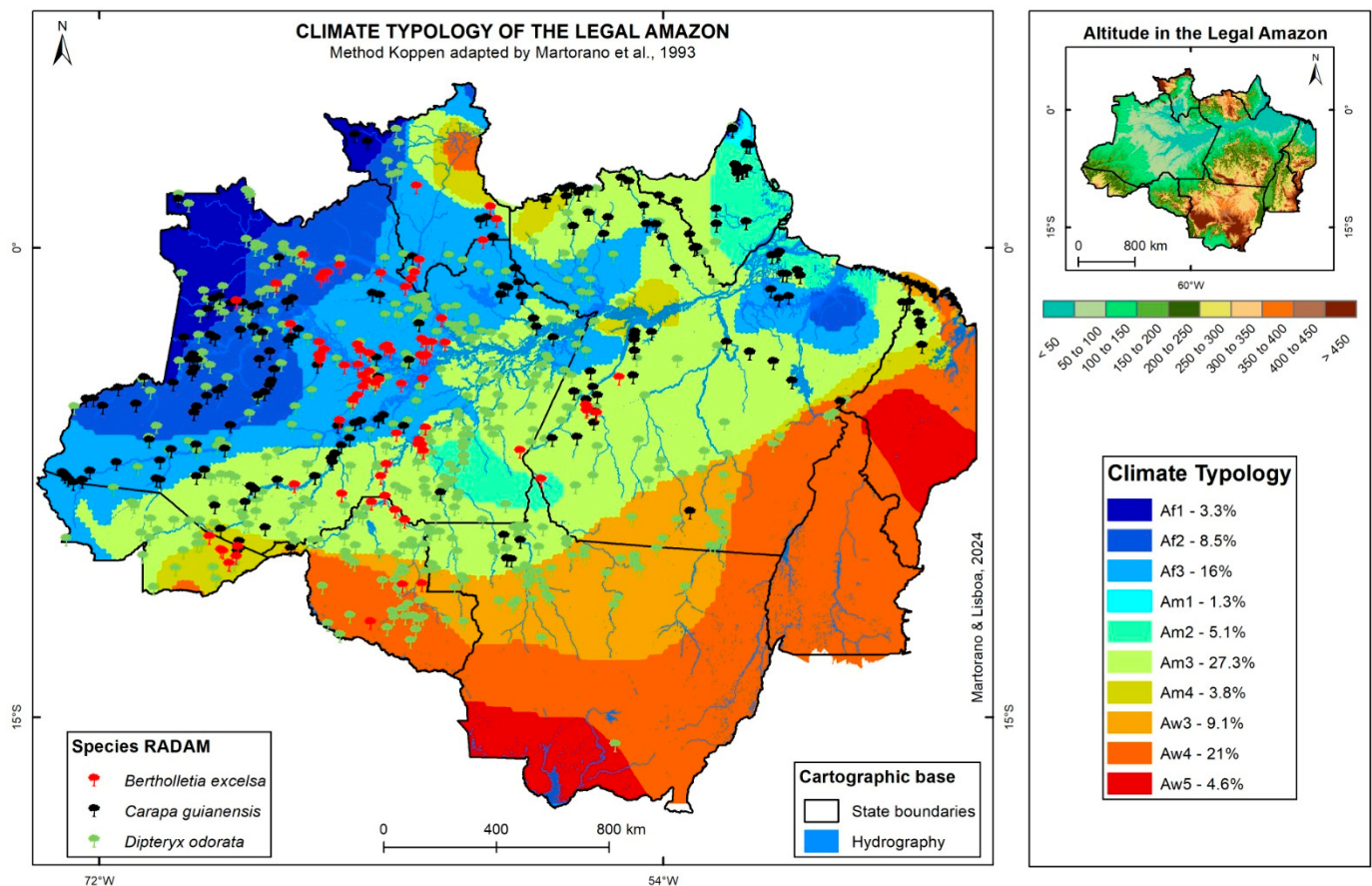


Figure 3. Climate typology map of the Legal Amazon using the methodology proposed by [56], adapted from [54], indicating the occurrence points of the three species recorded in the RADAMBRASIL project.

In the transition, there is the occurrence of Am₁ (1.3%), in which annual precipitation falls within values greater than 3000 mm, but in terms of the least rainy month, the values are below 60 mm, occupying a small portion of the region. In the Am₂ subtype (5.1%), annual rainfall varies between 3000 mm and 2500 mm, mainly in areas with climatic transition, occurring in parts of the Amazon where there is an influence of a slight dry season. Next appear the typical areas of Am₃ (27.3%), in which annual rainfall varies between 2500 mm and 2000 mm. It is noted that this is a subtype that is quite representative of the region. The presence of a longer dry season influences the type of vegetation and water dynamics but still allows the presence of forests with considerable biodiversity.

In the case of the Aw₃ subtype (9.1%), annual rainfall amounts vary between 2500 and 2000 mm, and these are areas of transition from the more typical savannah vegetation, where rainfall seasonality is marked, with dry periods that limit the diversity and density of forest cover. In the typical Aw₄ climate range (21.0%), rainfall varies between 2000 and 1500 mm, where this subtype occurs most abundantly in the Brazilian Amazon, indicating broad climatic adaptation in the vegetation.

The predominance of areas under this regime suggests that seasonality and drought are important factors in the regional environmental configuration. In Aw₅ (4.6%), the areas receive the least rainfall, with annual values ranging from 1500 to 1000 mm. These zones are generally associated with ecosystems that are more adapted to drought, such as cerrado and savannas, with vegetation adapted to prolonged periods without rain. It is worth

highlighting that in the works of [16–18], it is possible to observe the application of the topoclimatic zoning methodology for the native Amazonian species Parica (*Schizolobium amazonicum*) and Taxi-Branco (*Tachigali vulgaris* L.F. Gomes da Silva & H.C.).

It should be noted that in the Legal Amazon, 10 altimetric classes were separated and used to evaluate the potential areas for the three forest species evaluated. The altitude map in the upper right corner indicates that the highest altitudes (>450 m) are concentrated on the southern edge of the Legal Amazon, mainly in the state of Mato Grosso.

The lowest areas (<50 m) predominate in the center and north of the region, such as in Amazonas and Pará, reflecting the flat terrain of the Amazon basin. Areas with altitudes above 250 m are reported to be found in the states of Pará, Tocantins, Mato Grosso, Maranhão, Rondônia, Roraima, Acre, and Amapá. According to [74], projections for the end of the 21st century indicate significant changes in the distribution of climate types, with direct impacts on the sustainability of tropical ecosystems.

It is important to emphasize that all the maps presented below indicate only the areas with topoclimatic potential for each analyzed species in regions where vegetation loss has occurred due to human-induced disturbances. The zoning specifically highlights areas that have already been altered (anthropized), reinforcing their potential for species reintroduction and ecological restoration in priority zones. Therefore, the uncolored (white) areas do not imply a lack of occurrence data or ecological potential. Instead, they represent regions that remain non-anthropized and, consequently, are not included in the zoning, as the objective is to support strategic restoration efforts in degraded landscapes

The topoclimatic zoning of *Carapa guianensis* present highlights the wide adaptability of the species to different climatic and topographic conditions in the Legal Amazon (Figure 4). Areas with high potential occur in most of the area, accounting for 63.9% of the territory of the Legal Amazon. These regions present favorable conditions for the development of the species, according to climatic and topographic variables, indicating conditions for the growth and survival of Andiroba trees. Areas with high potential are widely distributed, especially along river basins, which may indicate a preference for environments with good water availability.

Medium potential is found in approximately 30.5% of the area, showing that topoclimatic conditions have restrictions on the development of *C. guianensis*, such as altitude variation or seasonal rainfall. This level of potential is distributed in transition zones between high and low potential and in some areas further south of the Legal Amazon. Only 5.6% of the total area was classified as having low potential. These areas are characterized by unfavorable conditions for the species, primarily due to altimetric factors and reduced water availability. Such areas are predominantly located in higher-altitude regions, particularly in the southern and eastern portions of the study area.

When analyzing the occurrence points of *Carapa guianensis* based on data from herbarium collections, literature, and the GBIF database, it becomes clear that the records are widely distributed, especially in areas identified as having high and medium topoclimatic potential. This pattern underscores the accuracy of the model, which estimated the topoclimatic potential for this species with notable precision and parsimony.

In contrast, when focusing on occurrence points derived from the RADAMBRASIL dataset, it is evident that these points are predominantly concentrated in areas classified as having high potential. This consistency across data sources reinforces the validity of the model and its ability to accurately predict suitable topoclimatic conditions for *C. guianensis*.

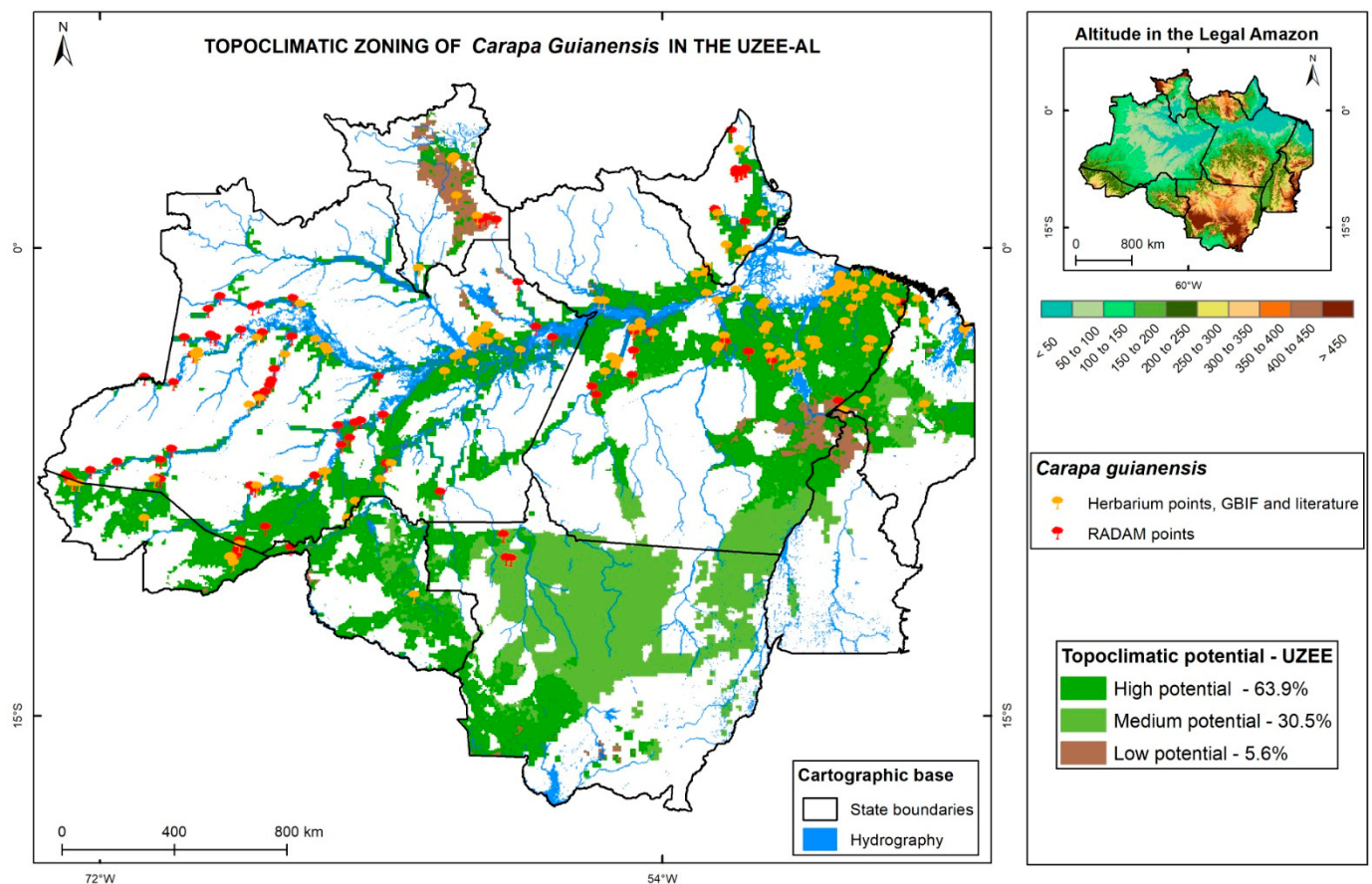


Figure 4. Map of the topoclimatic zoning of Andiroba (*Carapa guianensis*) in anthropic areas in the Legal Amazon.

It is also clear that areas with low altitude (<50 m), mainly near the main rivers, are the most favorable for recommending the cultivation of *C. guianensis*, based on topoclimatic conditions. On the other hand, areas with high altitude (>450 m), located in parts of Mato Grosso and Maranhão, are associated with low potential on the map.

Therefore, sustainable cultivation and management of the species is recommended, being the most suitable for the installation of projects that seek to include Andiroba in productive forests, or in other silvicultural actions in the Amazon, including *C. guianensis* in the menu of selected species, especially when the focus is on strengthening the bioeconomy in the region.

Zoning aims to subsidize conservation policies, support decisions on sustainable management, and target areas that have the greatest potential for strengthening the value chain of this important species known in the region by its vernacular name, Andiroba.

The results of the topoclimatic zoning indicate that *Dipteryx odorata* has high potential in 71.9% of the area of the Brazilian Amazon according to the topoclimatic conditions (Figure 5). Relief and moderate water availability are crucial factors for maintaining the productive potential of this species. Areas with medium potential are in 25.6% of the total area, due to limitations such as a longer dry season or higher altimetric levels. Low potential was identified in 2.5% of the area.

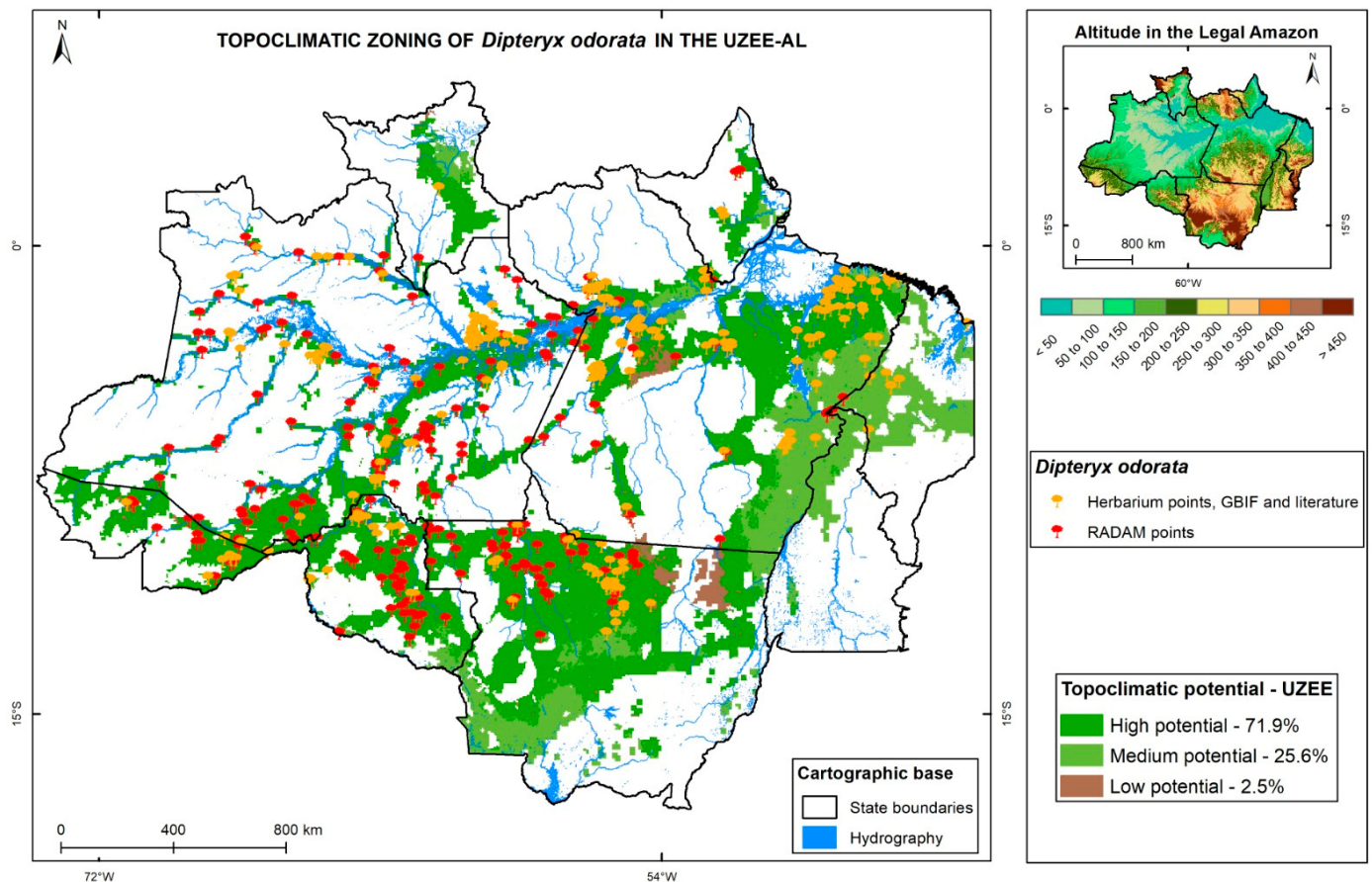


Figure 5. Map of the topoclimatic zoning of Cumaru (*Dipteryx odorata*) in anthropic areas in the Brazilian Amazon.

The occurrence locations identified in herbaria, the literature, and GBIF indicate that *D. odorata* has a wide geographic distribution, confirming its suitability to these environmental conditions. The RADAMBRASIL points reinforce the presence of the species in areas of high and medium potential, with some occurrences also in transition zones, which suggests a certain ecological flexibility of the species.

Dipteryx odorata is a key species for sustainable development in the Amazon, given its bioeconomic value and ecological importance. Topoclimatic zoning indicates that the species is widely adapted to the Amazonian climate, especially in areas of high humidity and low climatic seasonality. This mapping is essential for planning sustainable use policies, as it allows identifying priority areas for the cultivation, management, and conservation of the species.

The high density of the wood makes the logging of *D. odorata* an attractive economic activity, but it also presents risks of overexploitation. Management of the species should consider sustainable practices that include both controlled logging and harvesting of the almonds, thus promoting logging that preserves native populations and encourages the development of commercial Cumaru plantations.

The identified topoclimatic potential aims to indicate preferential areas for reforestation and recovery of degraded areas, using *D. odorata* as a native species with high plasticity and commercial value that should be taken into consideration in actions aimed at strengthening the regional bioeconomy. The topoclimatic zoning of *Bertholletia excelsa* in the Legal Amazon reveals a significant variation in areas of high, medium, and low potential for the growth of the species, with important implications for its conservation and management.

As a large tree, *Bertholletia excelsa* is important to the Amazon bioeconomy. The almonds are highly nutritious and have a high market value, including guaranteed world-wide export. In addition, the species play an important ecological role, helping to conserve biodiversity and providing relevant ecosystem services, such as soil maintenance and nutrient cycling. The species is on the list of endangered species due to intensive exploitation and destruction of its habitat, which makes topoclimatic zoning an opportunity to indicate areas suitable for restoration.

It is observed that 48.2% of the Brazilian Amazon has high potential for cultivating the species. These areas are widely distributed, especially in central regions and near large river basins, where favorable humidity levels and soil conditions support optimal growth and development. In 51.6% of the area, there are topoclimatic restrictions that include them in the medium potential condition. Restrictive topoclimatic conditions are associated with more pronounced dry periods or variations in altitude.

These areas can still support populations of chestnut trees but are less favorable to growth and productivity when compared to areas with high potential. In 0.2% of the area already anthropized, the cultivation of *B. excelsa* is not recommended. The distribution of occurrence points predominantly aligns with areas classified as having high to medium potential, highlighting the suitability of these regions for the species' establishment and growth.

The RADAMBRASIL points reinforce the presence of the chestnut tree in specific regions, which indicates its adaptability to variable climatic conditions, within certain limits. The altitude chart, located in the upper right corner of the map, shows that most areas with high potential are located at altitudes below 300 m. Low-altitude areas, especially near large river basins, are where the species develops most favorably due to the high availability of water and suitable temperatures.

Considering its economic and ecological importance, zoning is a strategic resource for identifying priority areas for conservation and for promoting sustainable management systems. It is recommended that areas with high potential be directed towards sustainable collection practices, where environmental impact can be minimized, preserving the natural regeneration of the species. In transition areas, the conservation of mother trees and the use of agroforestry management techniques can contribute to increasing the resilience of the species to environmental variations.

Cultivating chestnut trees in degraded areas contributes to the recovery of the ecosystem but also offers economic benefits to local communities through the collection of chestnuts. According to [41], it has 2.3 million km² potentially suitable for the cultivation of Brazil nuts. Areas with high potential for the three species studied can be included among the species with the greatest gaps for restoration, as [14]. The distribution and habitat focusing on soil–plant–atmosphere interactions indicate that the potential can be used in studies focused on ecological aspects aimed at the sustainable use of species with greater added value to non-timber products.

Carapa guianensis has a social contribution in the region, where the local market may not be strengthening the value chain of people who collect the seeds and extract oils, in an artisanal way. Among the strategies for strengthening these chains would be supported by Brazilian governance, where the law on payment for environmental services could foster the development of agro-industries [75], ensuring the strengthening and expansion of production systems, based on the region's biodiversity.

A study conducted in a protected area in Macapá, between October 2009 and October 2011, indicated that there was a proportion of trees with leaf change (new leaves and leaf fall) within the studied population of *C. guianensis*, in the state of Amapá, associated with the rainfall regime. The authors detected that in December 2009, there were buds in 83% of

the trees, followed in the months of September and October, when in 2010 90% of the trees were counted. In September 2011, flowering occurred in 100% of the monitored individuals, indicating a significant negative relationship between flower buds, flowering and the total monthly precipitation [76].

The native chestnut trees in the Brazilian Amazon predominate in the Argisols and Latosols classes [76], with 20% in the state of Mato Grosso occurring in Neossolos. These authors verified the presence of chestnut trees in ombrophilous forests, predominant (more than 70%) in the states of Acre, Amapá, Amazonas, and Pará. In Mato Grosso, they were in this forest typology in 50%. Throughout the Amazon, chestnut trees predominate in altimetric quotas below 200 m and annual rainfall ranging from 1500 mm to 2500 mm and average annual temperature, predominantly between 25.5 °C and 26.5 °C and above 27.0 °C, and air humidity range ranging from 75% to 85%.

Analyzing areas with high, medium, and low potential for the development of sustainable practices, it is evident that regions with high potential for integrated forestry are predominantly located in the states of Pará and Maranhão. In contrast, extensive areas in Amazonas and Acre are categorized as having medium potential (Figure 6). This spatial pattern reflects the influence of the topoclimatic variables analyzed, highlighting the critical environmental conditions that enable the productive development [77] of the forest species under study.

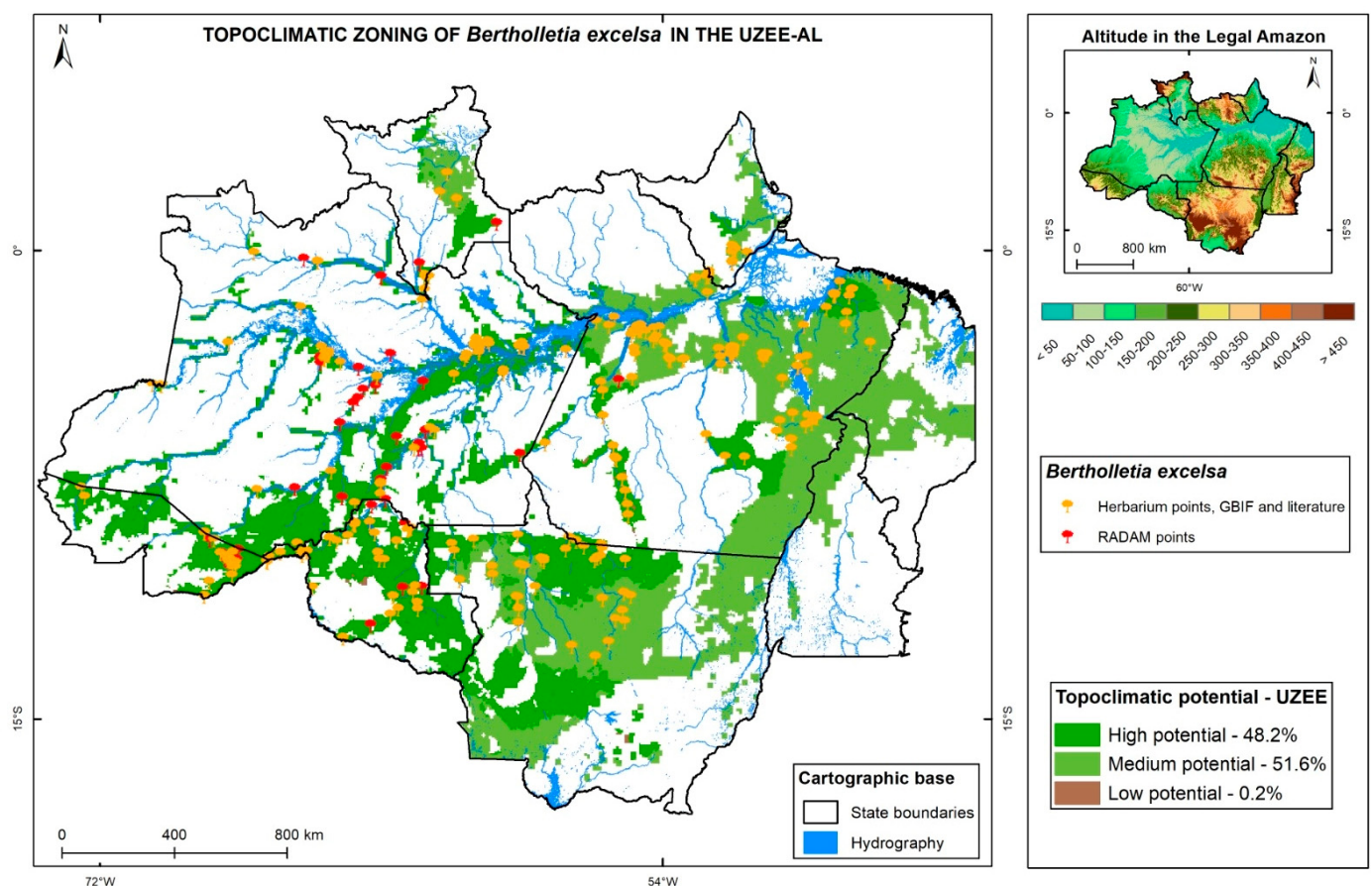


Figure 6. Map of the topoclimatic zoning of the Amazon nut (*Bertholletia excelsa*) in anthropic areas in the Legal Amazon.

Agroforestry systems have been widely promoted as a sustainable alternative to deforestation, as they enhance ecosystem resilience while providing local communities with viable and sustainable livelihood strategies. Forest zoning further contributes by offering a

range of benefits, including the conservation of water and soil resources, the promotion of certified management practices, and the reduction of conflicts arising from competing land uses, such as conservation areas versus productive zones. This integrated approach underscores the importance of strategic planning in balancing ecological sustainability with economic development [78].

These strategies are essential to promote the resilience of the Amazon rainforest in the face of climate change and to generate economic opportunities that value the region's ecosystem services, such as carbon capture and biodiversity conservation. This type of analysis is essential in the Amazon context, where the expansion of production systems focused on environmental conservation and sustainability is highly relevant [79].

The product offered is the result of work in integrating different areas, mainly in agrometeorology, geomatics, forestry engineering, and statistics. The graph in Figure 7 provides a summary of the key steps in the analysis. Specifically, it illustrates that among the statistical techniques employed, the silhouette graph and principal component analysis were utilized to identify the 18 groups of explanatory variables for the model. Subsequently, the map layer (Information Plans) demonstrates the use of a Geographic Information System (GIS) to derive topoclimatic zoning for each forest species. In this study, TopZon was applied to three forest species native to the Brazilian Amazon. However, the methodology is adaptable and can be applied to a wide range of forest species worldwide.

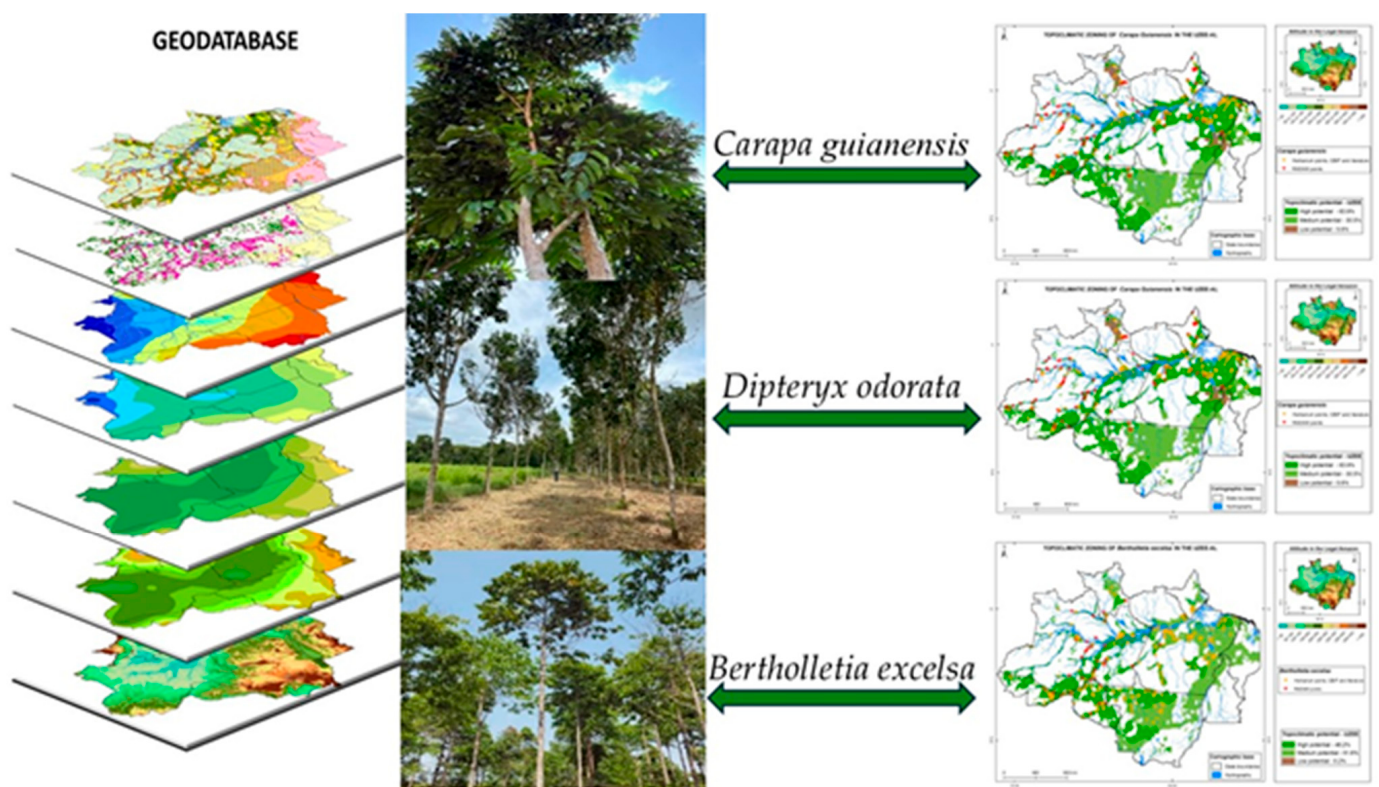


Figure 7. Integrated Information Layers for Topoclimatic Zoning of Native Amazonian Forest Species: A Synthesis Map Approach.

This study utilizes Geographic Information System (GIS) and statistical analysis, specifically silhouette graphs and principal component analysis, to determine topoclimatic zones for native Amazonian tree species. GIS plays a crucial role in mapping and visualizing the distribution of tree species across topoclimatic zones, helping to delineate suitable areas for each species based on environmental variables. Topoclimatic zoning is essential for under-

standing the specific environmental conditions needed for the growth and conservation of different species. These species are particularly valued for their diverse applications [80]:

Bertholletia excelsa (Castanha-da-Amazônia): Known for its nutritional benefits, the Castanha-da-Amazônia is widely used in the culinary industry for its high protein content and healthy fats [81].

Carapa guianensis (Andiroba): This species is prized in the cosmetics industry for its anti-inflammatory and healing properties, making it a key ingredient in natural skin care products [82].

Dipteryx odorata (Cumaru): Commonly known as the Tonka bean, Cumaru is highly sought after in both culinary and therapeutic fields due to its aromatic properties, which are used in perfumes and natural remedies [83].

Based on the work of [84], areas with forest plantations demonstrate significant potential to benefit from Brazil's Payment for Environmental Services (PES) Law. This legal framework enhances opportunities to integrate tools like TopZon into forest restoration strategies in the Brazilian Amazon. By identifying regions where high ecosystem service values cluster, such approaches can strengthen decision-making processes and promote sustainable land management practices. This alignment supports biodiversity conservation while providing economic incentives for stakeholders, fostering broader adoption of restoration initiatives across the Amazon biome.

The identification of potential areas for specific species through topoclimatic zoning offers significant opportunities to adopt sustainable planting strategies, such as integrated agroforestry systems and mixed-species plantations in high-potential zones. As highlighted in [85], integrating agriculture and forestry represents a sustainable approach to land use in the Brazilian Amazon. These strategies not only enhance environmental services, including carbon sequestration and biodiversity

The integration of these species into reforestation and agroforestry systems in the Brazilian Amazon goes beyond mere environmental restoration [18,85]. It serves as a strategic approach to bolster the bioeconomy by diversifying income sources for local communities, promoting sustainable land use, and supporting industries such as food, cosmetics, and pharmaceuticals.

This information is crucial for sustainable forest management and restoration efforts in the Brazilian Amazon. While this study focuses on three native Amazonian species, the methodology is universally applicable and can be extended to various forest species worldwide, offering valuable insights into conservation and land-use planning globally.

4. Conclusions

This study reaffirms the importance of applying the benefits of forestry species by identifying areas with high topoclimatic potential for *Carapa guianensis*, *Dipteryx odorata*, and *Bertholletia excelsa*. The topoclimatic zoning serves as a scientific contribution to support decision-making strategies for sustainable planting in anthropized areas of the Brazilian Amazon.

Carapa guianensis (Andiroba): Demonstrates strong adaptability in riparian zones, reinforcing its strategic use in bioeconomic projects and restoration efforts. The zoning reinforces that this species demonstrates high adaptability in humid zones, as areas with high water deficits limit the expression of the genetic potential of this native species. Projects aimed at strengthening the bioeconomic value chain of *Carapa guianensis* should recommend planting this species in areas identified as having high potential.

Dipteryx odorata (Cumaru): Compared to the other two species studied, *Dipteryx odorata* (Cumaru) shows the highest potential for widespread planting, with approximately 72% of high-potential areas located in anthropized regions of the Amazon. Beyond its well-known

timber potential in the region, Cumaru is gaining prominence in pharmaceutical, cosmetic, and culinary markets due to the value of its seeds, similar to the Amazon nut. Including this species, particularly in agroforestry systems, is strategically important.

Bertholletia excelsa (Amazon Nut): The Amazon nut (*Bertholletia excelsa*) was the species with the smallest areas of high potential compared to others, reinforcing its selective capacity. As one of the species listed as endangered in the region, including *Bertholletia excelsa* in forest plantations within approximately 48% of high-potential areas represents an excellent conservation strategy. These initiatives align with and can be effectively supported through programs established under the Payment for Environmental Services (PES) Law.

The zoning presented in this study reinforces that the best decision-making strategies for including these three species in sustainable forest plantations rely on prioritizing areas with high potential. Conversely, areas with medium potential may require strategies such as irrigation, as variables representing water availability constraints were consistently present in all topoclimatic zoning models for the three species. This is a strong indicator that native Amazonian species cannot withstand prolonged dry periods in the region.

Aligning the zoning findings with Brazil's Payment for Environmental Services Law could provide economic incentives for sustainable forestry practices. Integrating these species into agroforestry systems offers a dual benefit: fostering local livelihoods and enhancing biodiversity conservation.

Author Contributions: Conceptualization and methodology, L.G.M.; geomatic analysis, L.S.S.L.; data climatic analysis, L.G.M., J.R.d.S.C.d.M. and R.F.d.L.; statistical analysis, C.T.d.S.D., W.N., L.G.M., J.R.d.S.C.d.M. and L.S.S.L. and T.M.S.; literature review and geographical coordinate identification, D.L.C. and K.R.d.S.M.; searches for occurrences in herbariums and other repositories D.L.C., K.R.d.S.M. and T.M.S.; writing—original draft preparation, L.G.M.; writing—review and editing, L.G.M., S.B.J., J.R.d.S.C.d.M., L.S.S.L., C.T.d.S.D., W.N. and T.M.S.; supervision and project administration L.G.M. and S.B.J. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: Lucietta Guerreiro Martorano is employed by the Brazilian Agricultural Research Corporation (EMBRAPA Eastern Amazon), and Silvio Brienza Júnior is employed by the Brazilian Agricultural Research Corporation (EMBRAPA Forestry). The authors affirm that this work was conducted as part of a collaborative scientific partnership to strengthen a research network. They further declare that no conflicts of interest are associated with this study.

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