forests

MDPI

Article

Topoclimatic Zoning in the Brazilian Amazon: Enhancing Sustainability and Resilience of Native Forests in the Face of Climate Change

Lucietta Guerreiro Martorano [1,*], Silvio Brienza Junior [2], Jose Reinaldo da Silva Cabral de Moraes [3], Werlleson Nascimento [4], Leila Sheila Silva Lisboa [5], Denison Lima Correa [6], Thiago Martins Santos [7], Rafael Fausto de Lima [8], Kaio Ramon de Sousa Magalhães [9] and Carlos Tadeu dos Santos Dias [4,10]

1 Middle Amazon Technology Support and Transfer Center, Brazilian Agricultural Research Corporation (Embrapa) Eastern Amazon, Santarém 69010-180, PA, Brazil
2 Embrapa Forestry, Colombo 89540-010, PR, Brazil; silvio.brienza@embrapa.br
3 Sombrero Insurance, São Paulo 04730-000, SP, Brazil; reinaldojmoraes@gmail.com
4 Department of Exact Sciences, Luiz de Queiroz College of Agriculture, University of São Paulo, Piracicaba 13418-900, SP, Brazil; werlleson.nascimento@gmail.com (W.N.); ctsdias@usp.br (C.T.d.S.D.)
5 Municipal Secretary of Education—SEMEC, Belém 66123-030, PA, Brazil; lisboa.leilass@gmail.com
6 Department of Wood Technology (DTM), State University of Pará, Paragominas 68626-713, PA, Brazil; denison.correa@uepa.br
7 Department of Forest Sciences, School of Forest Engineering, Federal University of Lavras, Lavras 37200-900, MG, Brazil; eng.thiagomartins17@gmail.com
8 Department of Exact Sciences, School of Agricultural and Veterinarian Sciences, Paulista State University (UNESP), Jaboticabal 14883-378, SP, Brazil; rf.lima@unesp.br
9 Department of Forest Sciences, Federal University of Lavras (UFLA), Lavras 37200-900, MG, Brazil; kaiomagalhaesengflorestal@gmail.com
10 Department of Statistics and Applied Mathematics (DEMA), Federal University of Ceara, Fortaleza 60440-900, CE, Brazil
* Correspondence: lucieta.martorano@embrapa.br

check for updates

Academic Editor: Ernesto I. Badano

Received: 4 May 2025
Revised: 6 June 2025
Accepted: 10 June 2025
Published: 17 June 2025

Citation: Martorano, L.G.; Brienza Junior, S.; Moraes, J.R.d.S.C.d.; Nascimento, W.; Lisboa, L.S.S.; Correa, D.L.; Santos, T.M.; Lima, R.F.d.; Magalhães, K.R.d.S.; Dias, C.T.d.S. Topoclimatic Zoning in the Brazilian Amazon: Enhancing Sustainability and Resilience of Native Forests in the Face of Climate Change. *Forests* **2025**, *16*, 1015. https://doi.org/10.3390/f16061015

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Abstract: The Brazilian Amazon, a global biodiversity hotspot, faces escalating anthropogenic pressures and climate change, underscoring the urgent need to identify priority areas for ecological restoration and sustainable forest use. This study applied a topoclimatic zoning methodological framework in the Legal Amazon to evaluate the environmental suitability of 12 native tree species across anthropogenically altered landscapes. Species occurrence data were compiled from the RADAMBRASIL Project, GBIF, Herbaria, and forest inventory literature. Climatic, topographic, and geographic variables (1961–2022) informed the zoning model. Our findings reveal that species such as *Dinizia excelsa* Ducke (81%) and *Handroanthus albus* (Cham.) Mattos (78%) exhibit exceptionally high topoclimatic suitability. Conversely, *Simarouba amara* Aubl. (37%) and *Schizolobium parahyba* (Vell.) S.F.Blake var. *amazonicum* (Huber ex Ducke) Barneby (46%) showed the lowest proportions in high-potential areas, suggesting their greater ecological breadth or specific niche requirements in altered zones. Principal Component Analysis (PCA) indicated strong correlations between high-potential areas and Af3, Am3, and Aw4 climatic subtypes. This study offers a replicable, evidence-based model for prioritizing species and locations, significantly supporting sustainable silviculture and enhancing the long-term resilience of Amazonian forests in the face of climate change.

Keywords: TopZon; native silviculture; anthropogenic areas; indication of potentials

1. Introduction

The Brazilian Amazon, one of the largest forest ecosystems in the world, harbors a biological diversity of global significance. Within this vast expanse, numerous native forest species play fundamental roles not only in maintaining ecological integrity but also in driving the region's socioeconomic development. Maintaining areas of secondary forest is projected to secure annual carbon stocks of 19.0 Tg C^{-1} by 2030, based on 2017 data, representing approximately 5.5% of Brazil's net emissions [1,2]. Therefore, the adoption of legal mechanisms to protect and expand these areas should be encouraged as a climate solution grounded in the region's environmental responses [3,4].

A comprehensive review of China's major forest ecology projects and its carbon market under the carbon neutrality framework highlights that forestry possesses substantial potential as a carbon sink, offering both economic and environmental advantages [5]. Forestry contributes to biodiversity recovery and notably reduces vulnerability to natural disasters, reinforcing the relevance of this research focused on the Brazilian Amazon.

Areas rich in native forest species fulfill multiple ecological functions by delivering provisioning, regulatory, supporting, and cultural ecosystem services. The silviculture of native species offers opportunities to strengthen the bioeconomy and generate co-benefits through programs such as payments for environmental services, carbon markets, sustainable territories, and other national initiatives. Selecting species adapted to the Amazon's climatic and edaphic conditions is essential to ensuring effective forest management and sustainable resource use [6]. Each species performs differently depending on soil characteristics, altitude, and precipitation regimes.

Dinizia excelsa Ducke (angelim vermelho), for example, holds significant economic value in the timber market and is widely used in high-quality veneer and furniture production. *Copaifera* spp. (copaíba) stands out for its oleoresin extraction, which is highly valued in the pharmaceutical and cosmetic industries due to its therapeutic properties. *Swietenia macrophylla* King (Mogno Brasileiro) is renowned for its premium wood, extensively used in luxury furniture manufacturing. Meanwhile, *Jacaranda copaia* (Aubl.) (parapará) is recognized for its ability to rapidly colonize degraded areas, making it well-suited for ecological restoration projects [7,8].

In addition to their economic relevance, these species also possess undeniable ecological value. Species such as *Virola surinamensis* (Rol. ex Rottb.) Warb. (ucuúba) and *Schefflera morototoni* (Aubl.) (morototó) play vital roles in Amazonian ecosystems by providing food and shelter for local fauna. The natural regeneration of these trees contributes to the maintenance of forest structure and ecological functionality, while also helping to mitigate the effects of deforestation [9]. Previous studies have highlighted the role of native forest species as key drivers of the Amazon's bioeconomy, emphasizing their relevance for income generation through timber and non-timber products, as well as their essential contribution to biodiversity conservation [10].

Building on this perspective, a more recent approach by [11] reinforces the role of topoclimatic zoning as a strategic tool to promote sustainability and forest resilience in the face of climate change. By identifying areas with favorable environmental conditions for key species, this methodology supports sustainable forest management and ecological restoration. Like the approach by [12] in identifying spatial patterns of climate risk in urban areas, this study is also grounded in the analysis of the spatial distribution of environmental variables to identify patterns of topoclimatic suitability for native forest species in the Brazilian Amazon.

Scientific advancements have sought to develop methodologies that identify ecological zones to support climate policies, as demonstrated by [13]. This study provides valuable insights for the formulation of public policies and forest management strategies that can

stimulate the region's bioeconomy without compromising long-term conservation goals in the context of climate change [14,15]. Therefore, this study aims to delineate topoclimatic zones suitable for twelve key native forest species across the Brazilian Amazon, thereby enhancing ecosystem sustainability and resilience in the face of climate change.

2. Materials and Methods

This study focuses on the Legal Amazon region, with potential for future expansion to other areas of silvicultural interest. The analysis was conducted using a combination of species occurrence records, climate data, topographic information, and statistical modeling to support topoclimatic zoning for native forest species.

The core dataset used to model species distribution was obtained from the Environmental Information Database (BDiA) of the Brazilian Institute of Geography and Statistics (IBGE). Additional occurrence records were sourced from the Global Biodiversity Information Facility (GBIF, www.gbif.org accessed on 10 December 2024), herbarium databases, and bibliographic repositories containing forest inventory data. These supplementary datasets were essential for validating the topoclimatic zoning (TopZon) model for each of the 12 trees forest species analyzed (*Bagassa guianensis* Aubl; *Copaifera multijuga* Hayne; *Cordia goeldiana* Huber; *Dinizia excelsa* Ducke; *Handroanthus albus* (Cham.) Mattos; *Jacaranda copaia* (Aubl.) D.Don; *Schefflera morototoni* (Aubl.); *Schizolobium parahyba* var. *amazonicum* (Huber ex Ducke) Barneby; *Simarouba amara* Aubl.; *Swietenia macrophylla* King; *Virola surinamensis* (Rol. ex Rottb.) Warb.; *Vochysia maxima* Ducke), totaling 7643 georeferenced occurrences.

The climatic data were derived from the Brazilian Daily Weather Gridded Data (BR-DWGD), a high-resolution dataset in NetCDF format (0.1° × 0.1° grid), covering 41,115 virtual stations across the study area. The dataset spans the period from 1961 to 2022 [16,17] and includes daily records of precipitation, minimum, maximum and average temperatures, solar radiation (MJ m^{-2} day^{-1}), wind speed at 2 m height (m s^{-1}), potential evapotranspiration (mm), and relative humidity (%).

To perform the analysis, environmental layers were generated for each climatic variable. These included total annual rainfall (TAR), total rainfall in the driest quarter (TLRQ), rainfall in months with less than 100 mm (RF < 100 mm), and rainfall in months with less than 60 mm (RF < 60 mm). Temperature metrics included maximum (TMx), average (TAvg), and minimum (TMin). Additional variables such as relative humidity (RH), vapor pressure deficit (VPD), and Standardized Precipitation Index (SPI) were also incorporated, along with variables derived from the climatological water balance (CWB), including actual evapotranspiration (ETP), water stress (WST), and water surplus (WSP). The CWB was calculated assuming a readily available water (RAW) value of 300 mm.

Topographic (altitude) and geographic (longitude and latitude) data were also included in the analysis, as these are essential for understanding species distribution and adaptive capacity in response to environmental gradients. The vapor pressure deficit (VPD) was calculated as an indicator of potential water stress. Elevated VPD values are associated with greater evapotranspiration demand, potentially leading to stomatal closure and decreased photosynthetic activity. The Standardized Precipitation Index (SPI) was used to characterize the frequency and severity of dry periods relative to wetter conditions.

The climate typology employed in this study is based on the Köppen classification system, incorporating methodological adaptations proposed by [18] for tropical climates (type "A"), such as the Brazilian Amazon, where the mean annual air temperature exceeds 18 °C. These adaptations were comprehensively detailed by [11]; however, this work presents a synthesis as described below.

Considering the ecological specificity of the Amazon regarding rainfall availability, it was established that each precipitation range would span 500 mm. Thus, the climatic

subtypes defined by Köppen (Af, Am, Aw), traditionally classified based on the driest month (being greater than 60 mm for Af) and (less than 60 mm for Am and Aw), were refined to also incorporate the total annual precipitation. In this way, beyond stratification based on the driest month, the region's climate is highly influenced by the total annual rainfall. The numbering of the subtypes corresponds to the precipitation intervals is detailed in [11] but synthesized in this work to facilitate the understanding of the methodological adaptation proposed by [18,19], in which:

- Af—Fully humid climates ($p_dry \geq 60$ mm)
  - Af1: Annual precipitation > 3000 mm.
  - Af2: 3000 mm ≥ Annual precipitation > 2500 mm.
  - Af3: 2500 mm ≥ Annual precipitation > 2000 mm.
- Am—Monsoon climates ($p_dry < 60$ mm and $p_dry > \beta'$)
  - Am1: Annual precipitation > 3000 mm.
  - Am2: 3000 mm ≥ Annual precipitation > 2500 mm.
  - Am3: 2500 mm ≥ Annual precipitation > 2000 mm.
  - Am4: 2000 mm ≥ Annual precipitation ≥ 1500 mm.
- Aw—Savanna climates ($p_dry < 60$ mm and $p_dry \leq \beta'$)
  - Aw3: 2500 mm ≥ Annual precipitation > 2000 mm.
  - Aw4: 2000 mm ≥ Annual precipitation ≥ 1500 mm.
  - Aw5: Annual precipitation < 1500 mm.

2.1. Statistical Analysis

Topoclimatic zoning was conducted using multiple linear regression models applied individually to each species. These models integrated climatic variables (such as annual precipitation, average temperature, and relative humidity), topographic variables (such as altitude and slope), and species occurrence data. Occurrence information was obtained from the RADAMBRASIL Project [20], totaling 7643 data points, which were hierarchically grouped into internally homogeneous clusters to ensure the ecological representativeness of the analyzed species. This statistical approach enabled the identification of areas with varying levels of topoclimatic potential for the cultivation and restoration of forest species in the region, as detailed in [19].

The variable "Frequency", generated from this clustering process, was selected to represent species response behavior. The optimal number of clusters was determined by silhouette analysis, which indicated that 18 clusters offered the best fit.

Silhouette values range from -1 to 1. Values close to 1 indicate that the object is well-matched to its own cluster and poorly matched to neighboring clusters. Values around 0 suggest overlapping group boundaries, while negative values indicate potential misclassification. The purpose of this clustering step was twofold: (i) to group species with similar ecological responses to climatic and topographic conditions, and (ii) to provide a meaningful dependent variable for regression modeling. All input variables were standardized (mean = 0; SD = 1) prior to analysis.

With the dependent variable defined, a multiple linear regression analysis was applied using the cluster-based frequency means. Stepwise variable selection (both forward and backward) was employed to identify the most significant predictors. The final model was selected based on the lowest value of the Akaike Information Criterion (AIC).

The modeling approach incorporated both geographic and topographic variables (longitude, latitude, and altitude), as well as climatic predictors related to water availability, temperature variation, and atmospheric conditions. These included the following: water stress index (WST): a combined metric capturing climatic drought and evapotranspiration

dynamics; rainfall thresholds: number of months with rainfall below 100 mm (RF < 100) and below 60 mm (RF < 60), as indicators of seasonal water deficit; total annual rainfall (TAR) and total rainfall in the driest quarter (TLRQ): used to assess long-term and seasonal water availability; relative humidity (RH) and vapor pressure deficit (VPD): reflecting atmospheric moisture demand; Standardized Precipitation Index (SPI): a normalized drought indicator; temperature extremes and means (TMx, TAvg, TMin): indicating thermal suitability and stress conditions. Regression coefficients were interpreted to evaluate how each predictor contributed to the potential occurrence or environmental suitability of each forest species.

2.2. Topoclimatic Suitability Mapping

Principal Component Analysis (PCA) was applied to assess the degree of correlation among topoclimatic variables and to reduce data dimensionality, with the selection of representative variables based on the proportion of variance explained. This method also enabled the characterization of observations (i.e., native forest species) in relation to environmental gradients.

For each of the 12 native Amazonian tree species, multiple linear regression models were developed using a stepwise variable selection method. The predictor variables included climatic and environmental layers, such as annual precipitation (prpannual); total precipitation in months with rainfall below 60 mm (prp60); total precipitation in months with rainfall below 100 mm (prp100); maximum, mean and minimum air temperatures (tempmax, tmpmed, tmpmin); relative humidity (rh); Standardized Precipitation Index (spi); length of the dry season (trimenos); vapor pressure deficit (dpv); climatic water deficit (def); elevation (altitude); and spatial coordinates (latitude, longitude).

2.3. Topoclimatic Suitability Equations

Angelim-pedra (*Dinizia excelsa*) = −907.3962 + 3.3423 × longitude + 0.201 × def − 1.311 × prp60 − 0.0401 × prpannual + 15.4871 × rh − 0.2856 × dryseason + 117.6838 × vpd − 0.0974 × elevation.

Copaíba (*Copaifera multijuga*) = 3077.1170 + 2.7867 × longitude − 0.3832 × def − 0.0708 × prp100 + 1.3532 × prp60 − 0.0332 × prpannual − 14.9907 × rh + 6.3045 × spi + 155,263.1832 × tmax – 310,601.0180 × tmean + 155,286.4173 × tmin + 0.3154 × dryseason − 274.9635 × vpd − 0.2121 × elevation.

Tatajuba (*Bagassa guianensis*) = 1168.8506 + 5.1857 × longitude + 14.8098 × latitude − 1.2600 × def − 0.6676 × prp100 + 2.0430 × prp60 − 0.0348 × prpannual − 19.2385 × rh + 407,126.9500 × tmax – 814,176.6517 × tmean + 407,079.4051 × tmin − 0.8054 × dryseason + 85.3343 × vpd − 0.0473 × elevation.

Mogno brasileiro (*Swietenia macrophylla*) = −487.3907 − 2.2819 × longitude + 0.4977 × latitude + 0.0367 × def + 0.1845 × prp100 + 0.0403 × prpannual − 4.6196 × rh + 24.4582 × spi – 1,586,736.3925 × tmax + 3,173,481.4647 × tmean – 1,586,719.1213 × tmin − 0.0385 × dryseason + 10.1257 × vpd + 0.0790 × elevation.

Freijó (*Cordia goeldiana*) = −217.6567 + 0.3824 × longitude − 0.0211 × def + 0.0194 × prp60 + 0.9540 × rh − 3.5810 × spi – 123,318.3247 × tmax + 246,649.1180 × tmean – 123,326.3516 × tmin + 7.1082 × vpd + 0.0198 × elevation.

Quaruba (*Vochysia maxima*) = 4.5867 − 2.8295 × latitude + 0.1113 × prp100 − 0.6249 × prp60 − 0.0116 × prpannual + 26.3519 × spi − 14.0679 × tmax + 18.9008 × tmean.

Ipê Amarelo (*Handroanthus albus*) = 492.2552 − 6.0067 × longitude + 26.8858 × latitude + 0.4977 × def − 0.7012 × prp100 − 0.1944 × prpannual + 30.1898 × rh + 111.3414 × spi + 127.7833 × tmax − 244.8103 × tmean − 0.4892 × dryseason + 253.8842 × vpd − 1.0800 × elevation.

Parapará (*Jacaranda copaia*) = 2236.8447 + 2.4987 × longitude + 14.8318 × latitude − 0.3011 × def − 1.9760 × prp60 − 0.1272 × prpannual − 21.8551 × spi + 48.3450 × tmax − 106.4293 × tmean − 0.3772 × dryseason − 91.4789 × vpd − 0.4684 × elevation.

Marupá (*Simarouba amara*) = −145.6026 + 40.3134 × tmax − 40.3282 × tmean.

Ucuuba (*Virola surinamensis*) = −3092.9919 − 14.3109 × longitude + 4.7749 × latitude + 1.3442 × def + 0.0486 × prpannual − 79.6432 × spi + 78.0274 × tmean + 0.0140 × vpd.

Morototó (*Schefflera morototoni*) = −944.6943 + 6.4945 × longitude + 6.7747 × latitude − 0.7439 × def + 0.9063 × prp60 − 0.0438 × prpannual + 13.4594 × rh + 76.3397 × spi + 122.7637 × tmax − 130.4427 × tmean − 0.0019 × vpd − 0.1269 × elevation.

Paricá (Schizolobium amazonicum) = −324.5762 − 2.3514 × longitude + 5.8877 × latitude − 0.2694 × def − 0.1887 × prp100 + 1.2552 × prp60 + 0.0083 × prpannual − 5.7949 × rh + 47.2438 × spi + 26.3043 × tmax − 6.1095 × tmean + 0.0193 × dryseason − 19.2987 × vpd.

The regression coefficients obtained for each species were applied through map algebra in a Geographic Information System (GIS), resulting in continuous raster surfaces representing modeled topoclimatic suitability. These outputs were analyzed using frequency histograms and natural breaks to define thresholds that segmented the data into three suitability classes: high (top third of the values), medium (middle third), and low (bottom third). These categories were visualized in green, yellow, and brown, respectively.

2.4. Topoclimatic Zoning Validation

After constructing the topoclimatic zoning (TopZon) maps, a validation procedure was conducted to evaluate the coherence between the potential zoning classes and the regional climatic typologies defined by [18].

Topoclimatic potential areas (high, medium, low) for native forest species in the Amazon were delineated by integrating environmental variables into a geodatabase (GIS), structured through multiple regression models specific to each species. These models were based on occurrence points from the RADAMBRASIL project—an extensive forest inventory conducted during the 1970s and 1980s, when the Amazon was still considered a demographic void [21].

The methodology was rigorously validated using independent occurrence data obtained from herbarium collections, the Global Biodiversity Information Facility (GBIF), and additional bibliographic sources. Subsequently, multivariate statistical analyses—Principal Component Analysis (PCA) and K-means clustering—were applied to examine the distribution patterns of species in relation to the adapted Köppen climate typology [18].

A further step involved isolating anthropized areas based on data from the Ecological-Economic Zoning (UZEE), using spatial buffer techniques [22]. As an example, this methodology was applied within the UZEE Project to the species *Tachigali vulgaris* L.F. (Taxi-branco) [23], as well as to *Schizolobium amazonicum* (Paricá), for which the delineation of areas with favorable topoclimatic conditions supported the identification of priority zones for ecological restoration and forest planning actions, as demonstrated in [24,25].

2.5. Association Tests and Visualization

To test the relationship between topoclimatic potential and climatic typologies, categorical association tests were conducted using SAS OnDemand for Academics, SAS INC. (Cary, NC, USA) SAS FREE VERSION, 2025. The Chi-square test was used to assess the statistical significance of associations ($p < 0.05$ indicating significance), while Cramér's V and the Phi coefficient were calculated to assess the strength of the associations. A Cramér's V value near 0 indicates a weak association, whereas values approaching 1 indicate strong association. Similarly, the Phi coefficient ranges from −1 to 1, with values close to 1 or

−1 suggesting strong relationships. A biplot was also produced to visually explore the interaction between topoclimatic potential classes and climatic subtypes across the 12 native species analyzed.

ArcGIS for Desktop v10.2.2 software was used for map modeling and generating the raster layers and used to produce the final maps.

3. Results and Discussion

The topoclimatic zoning conducted for the twelve native forest species revealed spatial variability in their potential distribution across the Brazilian Amazon, categorized into three classes: high, medium, and low potential. Table 1 presents the percentage of each class identified for each species and offers a comparative overview of their ecological preferences.

Table 1. Topoclimatic zoning of 12 selected native tree species from the Brazilian Legal Amazon, including taxonomic authors.

Species	Author	High (%)	Medium (%)	Low (%)
Bagassa guianensis (BG)	Aubl.	65	26	9
Copaifera multijuga (CM)	Hayne	54	20	26
Cordia goeldiana (CG)	Huber	65	15	20
Dinizia excelsa (CE)	Ducke	81	15	4
Handroanthus albus (HA)	(Cham.) Mattos	78	14	8
Jacaranda copaia (JC)	(Aubl.) D.Don	75	14	11
Schefflera morototoni (SM)	(Aubl.) Maguire, Steyerm. & Frodin	60	31	9
Schizolobium parahyba var. amazonicum (SPA)	(Huber ex Ducke) Barneby	46	30	24
Simarouba amara (SA)	Aubl.	37	40	23
Swietenia macrophylla (SM)	King	74	10	16
Virola surinamensis (VS)	(Rol. ex Rottb.) Warb.	59	24	17
Vochysia maxima (VM)	Ducke	67	27	6

For instance, *B. guianensis* (tatajuba) exhibits a strong preference for areas with adequate water availability, with 65% of its mapped area identified as having high potential. Conversely, *C. multijuga* (copaíba), while adaptable, shows a slightly lower high-potential area (54%), indicating a greater sensitivity to specific environmental factors, particularly water availability, with the remaining area distributed between medium (20%) and low (26%) suitability. Similarly, *C. goeldiana* (freijó) demonstrates a broad adaptability, with 65% high potential, thriving best in regions with sufficient precipitation and soil moisture.

Species with particularly high topoclimatic potential include *D. excelsa* (angelim vermelho), with 81% high potential, demonstrating a strong affinity for optimal conditions, notably the hydrologically floodplain and igapó regions. *H. albus* (ipê branco) and *H. serratifolius* (ipê amarelo) also show extensive high potential areas (78%), highlighting their adaptability across diverse altitudes and precipitation regimes. *J. copaia* (parapará) follows closely with 75% high potential, suggesting its strong suitability for areas with favorable climatic conditions, making it a promising species for ecological restoration and forest regeneration initiatives.

In contrast, *S. parahyba* var. *amazonicum* (paricá) and *S. amara* (marupá) exhibit more restricted high-potential areas (46% and 37%, respectively), indicating a greater dependence on specific environmental conditions, particularly concerning soil moisture for paricá and optimal precipitation and soil moisture for marupá. *S. morototoni* (morototó) and *V. surinamensis* (ucuúba) show moderate high-potential areas (60% and 59%), suggesting a need for specific environmental conditions like adequate moisture and fertility for optimal growth. Finally, *S. macrophylla* (mogno brasileiro) and *V. maxima* (quaruba) display considerable

high potential (74% and 67%), reflecting their adaptability to moderate to high precipitation and varied environmental conditions, respectively.

The spatial patterns identified in Table 1 strongly suggest a prioritization of high-potential regions, particularly those along rivers and humid areas, for immediate and focused forest management and conservation interventions. While acknowledging the importance of medium and low potential areas for maintaining overall biodiversity, our analysis indicates that these regions, characterized by environmental constraints for the studied species, will require the development and implementation of more targeted and potentially assisted management strategies to ensure their effective conservation and sustainable use.

The topoclimatic zoning for the twelve selected native forest species, visually represented across Figures 1–3, provides an unprecedented level of detail on their ecological suitability within the anthropized landscapes of the Legal Amazon. These figures, read in conjunction with the precise percentages outlined in Table 1, serve as a fundamental tool for guiding evidence-based silvicultural strategies, enabling more effective cultivation, conservation, and restoration efforts within the framework of the Unified Ecological-Economic Zoning (UZEE) buffer.

Figure 1a–d delves into the topoclimatic potential of four key species: *Bagassa guianensis*, *Copaifera multijuga*, *Cordia goeldiana*, and *Dinizia excelsa*. For *Bagassa guianensis* (Figure 1a), the map predominantly highlights high topoclimatic potential, encompassing 65% of anthropized areas. This visually expansive high-potential zone signifies a robust environmental suitability, positioning *B. guianensis* as a priority species for large-scale silvicultural interventions aimed at forest restoration in deforested regions. Medium potential covers 26%, while only 9% is low, indicating a consistently favorable landscape for its development.

The zoning for *Copaifera multijuga* (Figure 1b) illustrates that 54% of anthropized areas within the UZEE buffer exhibit high topoclimatic potential. While substantial, the map also shows a notable presence of low potential (26%), suggesting a more geographically constrained optimal distribution. This spatial pattern emphasizes the need for careful site selection to maximize the success of silvicultural strategies and conservation efforts for this species in areas impacted by deforestation.

Cordia goeldiana (Figure 1c) presents a clear dominance of high potential, accounting for 65% of the anthropized buffer zones. This widespread suitability across deforested areas makes *C. goeldiana* a highly recommendable species for prioritization in silvicultural programs focused on areas aligning with the UZEE guidelines. Its moderate presence in medium (15%) and low (20%) potential zones further supports its general viability.

Dinizia excelsa (Figure 1d) stands out with a remarkable 81% of its distribution modeled as high topoclimatic potential within anthropized areas. This exceptional suitability, visually striking on the map, indicates that *D. excelsa* is profoundly adapted to a vast extent of available deforested lands. Such high-potential zones are unequivocally priority areas for ambitious silvicultural strategies, offering immense promise for high-productivity forest interventions and ecological restoration in regions previously impacted by deforestation. Medium and low potentials are minimal (15% and 4%, respectively), underscoring its precise ecological niche.

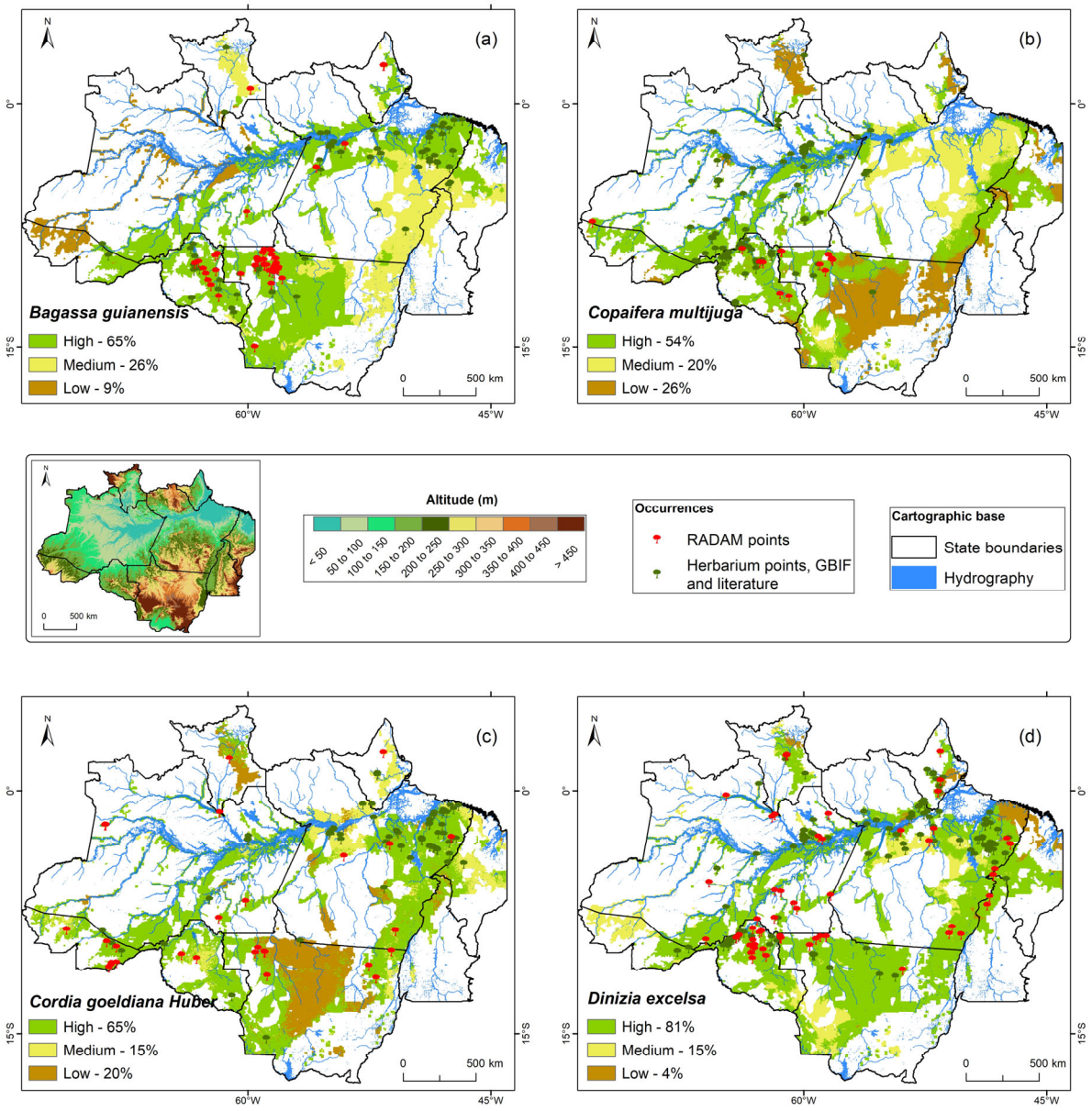


Figure 1. Topoclimatic zoning maps (**a**–**d**) of the following species in anthropized areas of the Legal Amazon.

Figure 2e–h further details the topoclimatic zoning for *Handroanthus albus*, *Jacaranda copaia*, *Schefflera morototoni*, and *Schizolobium parahyba* var. *amazonicum*. *Handroanthus albus* (Figure 2e) shows strong performance, with 78% of anthropized areas within the buffer presenting high topoclimatic potential. This substantial coverage across favorable zones positions *H. albus* as a cornerstone species for large-scale restoration initiatives and sustainable forest management, particularly where suitable environmental conditions for its robust establishment are present.

The maps for *Jacaranda copaia* (Figure 2f) reinforce its suitability, revealing 75% of anthropized areas with high potential, 14% medium, and 11% low. This consistent high suitability across widespread deforested areas makes *J. copaia* a reliable choice for reforestation and sustainable management initiatives, contributing to the ecological recovery of degraded Amazonian landscapes.

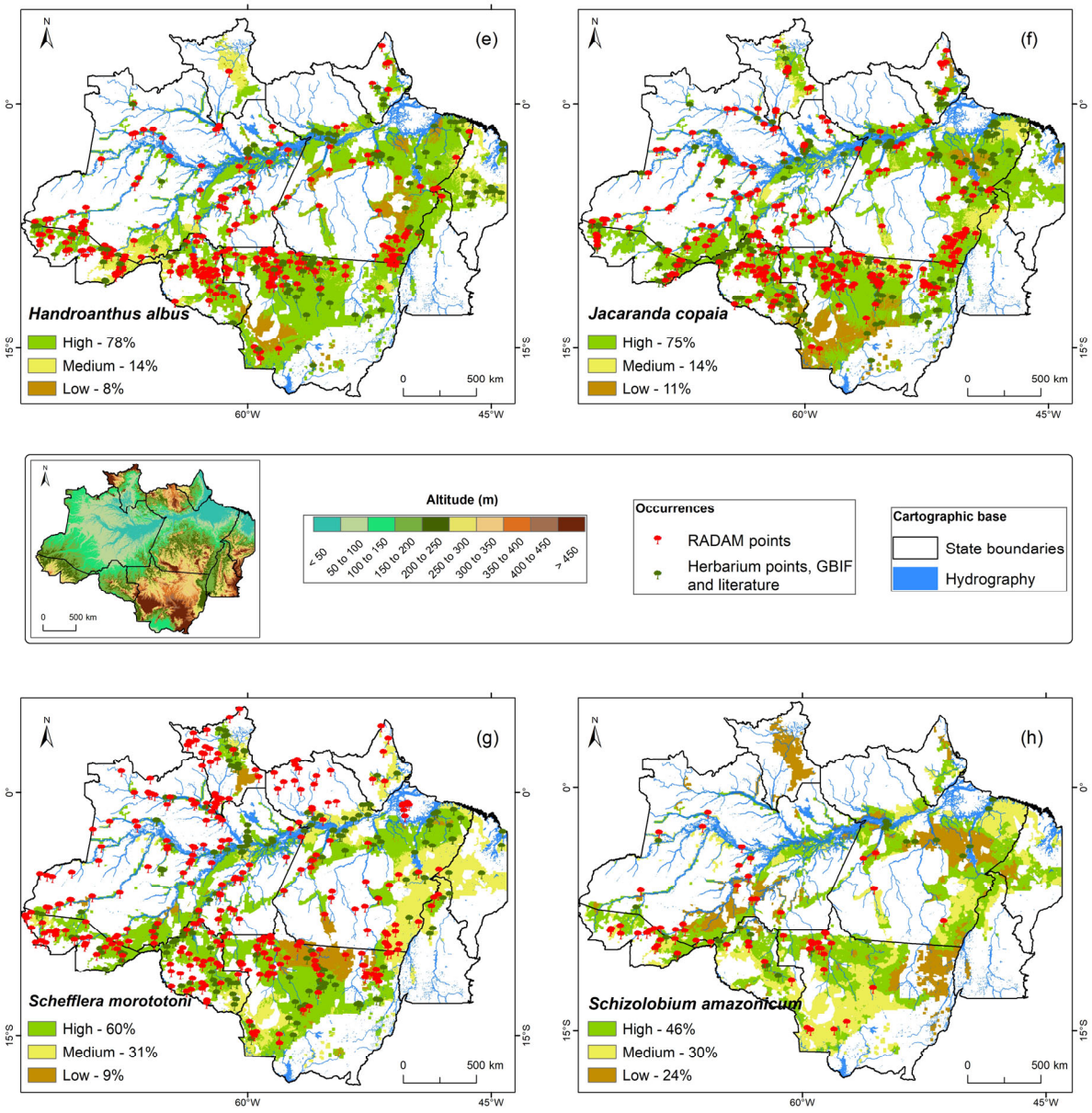


Figure 2. Topoclimatic zoning maps (**e**–**h**) of the following species in anthropized areas of the Legal Amazon.

For *Schefflera morototoni* (Figure 2g), 60% of the anthropized areas exhibit high topoclimatic potential, with a significant 31% in medium and 9% in low potential zones. This pattern, visible on the map, indicates a moderate variability in suitability but also broad possibilities for its integration into diverse restoration strategies, including those in moderately suitable environments, due to its adaptability. The distribution for *Schizolobium parahyba* var. *amazonicum* (Figure 2h) is more balanced, with 46% high, 30% medium, and 24% low potential. Visually, its map presents a more mosaic-like pattern of suitability. While the proportion of highly suitable zones is lower compared to other species, these results still highlight a significant area of favorable conditions for silvicultural adoption across anthropized landscapes. This balanced distribution suggests its robust performance in a broader range of environmental conditions, indicating significant ecological plasticity.

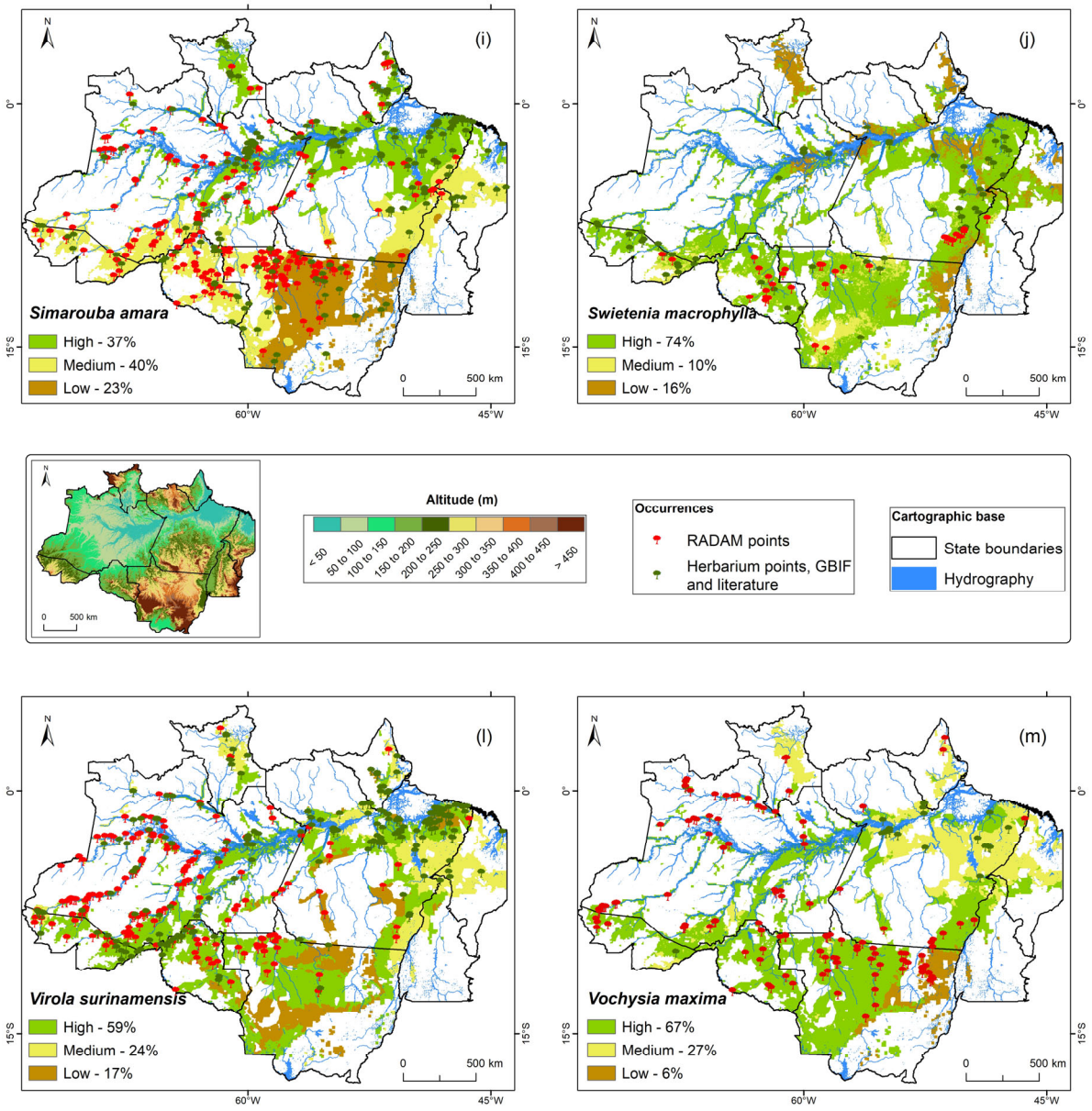


Figure 3. Topoclimatic zoning maps (**i**,**j**,**l**,**m**) of the following species in anthropized areas of the Legal Amazon.

Figure 3i,j,l,m completes the comprehensive topoclimatic zoning, illustrating the potential for *Simarouba amara*, *Swietenia macrophylla*, *Virola surinamensis*, and *Vochysia maxima*. *Simarouba amara* (Figure 3i) exhibits a unique distribution, with only 37% of anthropized areas classified as high potential, while 40% are medium and 23% are low. This relatively balanced spatial distribution, clearly depicted on the map, mandates a highly selective application of silvicultural strategies, emphasizing the crucial need for local suitability assessment before implementation. Its resilience across various conditions, however, offers strategic opportunities in diverse restoration contexts.

In contrast, *Swietenia macrophylla* (Figure 3j) shows a more favorable pattern, with 74% of anthropized zones identified as high potential, 10% as medium, and 16% as low. This strong environmental suitability, visibly concentrated in favorable areas on the map, confirms its robust potential for large-scale restoration efforts in deforested areas, particularly in regions where environmental conditions align with its optimal requirements.

Virola surinamensis (Figure 3l) presents 59% of anthropized areas with high potential, 24% medium, and 17% low. This distribution, shown visually, reinforces its strong viability for inclusion in various silvicultural programs across a wide range of previously degraded landscapes, allowing for flexible application based on local site conditions and restoration objectives.

Finally, *Vochysia maxima* (Figure 3m) demonstrates highly promising conditions, with 67% of its distribution modeled as high potential, 27% as medium, and only 6% as low. This translates into vast areas of favorable topoclimatic conditions within anthropized zones, making *V. maxima* one of the most suitable species for widespread implementation in restoration initiatives across the Legal Amazon.

Taken together, these detailed visual representations in Figures 1–3, coupled with the precise quantitative data in Table 1, offer an indispensable tool for evidence-based decision-making.

The values presented in Table 2 indicate that all species exhibited a statistically significant association with the climatic typologies ($p < 0.05$), suggesting that their distributions are not random, but rather influenced by specific climatic patterns. The Phi and Cramér's V coefficients, used to assess the strength of this association, revealed magnitudes ranging from moderate to moderately strong. The Phi coefficient varied from 0.5608 (for *C. multijuga*) to 0.6774 (for the remaining species), while Cramér's V remained constant at 0.3911 across all species, reinforcing the consistency of the detected associations. Specifically, *C. multijuga*, *J. copaia*, *S. parahyba* var. *amazonicum*, *S. amara*, and *V. surinamensis* showed moderate associations, whereas the remaining species exhibited moderately strong associations, indicating greater sensitivity to variations in the mapped topoclimatic conditions.

Table 2. Statistical analysis of forest species: significance ($p < 0.05$), Phi coefficient, Cramér's V, and strength of association.

Species	Statistical ($p < 0.05$)	Phi Coefficient	Cramér's V	Strength of Association
Bagassa guianensis	Significant	0.6774	0.3911	Moderate to Strong
Copaifera multijuga	Significant	0.5608	0.3911	Moderate
Cordia goeldiana	Significant	0.6774	0.3911	Moderate to Strong
Dinizia excels	Significant	0.6774	0.3911	Moderate to Strong
Handroanthus albus	Significant	0.6774	0.3911	Moderate to Strong
Handroanthus serratifolius	Significant	0.6774	0.3911	Moderate to Strong
Jacaranda copaia	Significant	0.6774	0.3911	Moderate
Schefflera morototoni	Significant	0.6774	0.3911	Moderate to Strong
Schizolobium parahyba var. *amazonicum*	Significant	0.6774	0.3911	Moderate
Simarouba amara	Significant	0.6774	0.3911	Moderate
Swietenia macrophylla	Significant	0.6774	0.3911	Moderate to Strong
Virola surinamensis	Significant	0.6774	0.3911	Moderate

Figure 4 provides an integrated visualization of climatic typologies, species groupings, and multivariate ecological relationships that structure the topoclimatic zoning of twelve native forest species in the Brazilian Amazon. The left portion of the figure displays the Köppen climatic typology map, adapted from [18], where species occurrence points are grouped into three categories (high, medium, and low) according to their topoclimatic potential as determined by the zoning model. This model was developed exclusively within anthropized areas, defined by the application of an anthropic buffer, and therefore excluded occurrence points located outside zones of consolidated land-use.

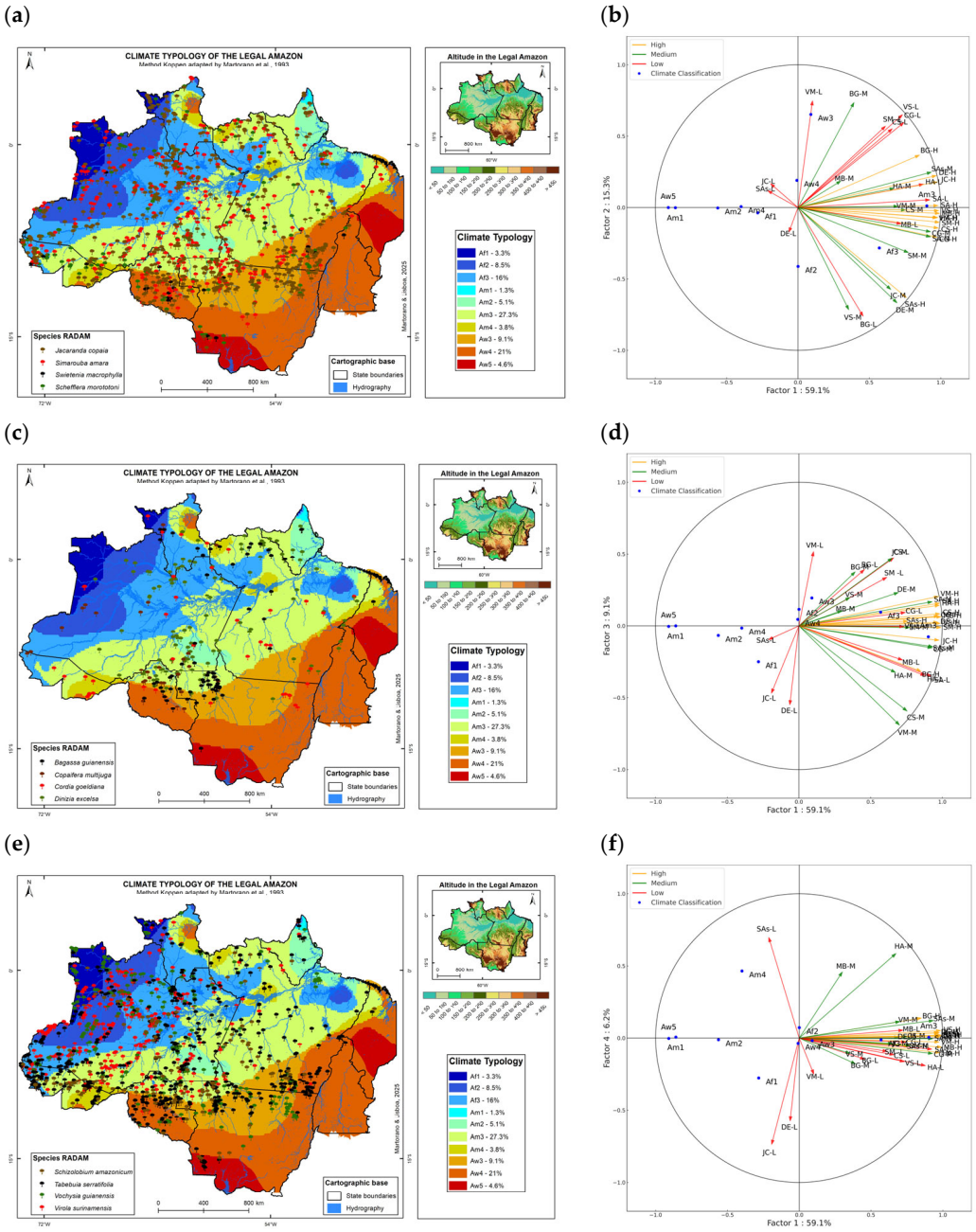


Figure 4. Spatial distribution of climate typologies in the Legal Amazon and multivariate analysis of forest species from the RADAMBRASIL database. (**a**,**c**,**e**) Maps of climate typologies in the Legal Amazon according to the Köppen classification adapted by [11,18], overlaid with the occurrences of different forest species from the RADAMBRASIL database. (**a**) *Jacaranda copaia*, *Simarouba amara*, *Swietenia macrophylla*, *Schefflera morototoni*; (**c**) *Bagassa guianensis*, *Copaifera multijuga*, *Cordia goeldiana*, *Dinizia excelsa*; (**e**) *Schizolobium amazonicum*, *Handroanthus serratifolius*, *Vochysia maxima*, *Virola surinamensis*. (**b**,**d**,**f**) Biplot graphs of Principal Component Analysis (PCA), showing the relationship between the distribution of the respective species and the different climate typologies.

This ensures that the ecological associations reflect species performance under realistic land–climate scenarios, directly relevant to reforestation and management planning. The spatial distribution of species grouped by potential demonstrates clear patterns of ecological affinity with specific climatic regimes. Species with high topoclimatic potential tend to concentrate in typologies such as Af2, Af3, and Am3, which correspond to humid and climatically stable areas, while those with low potential are found in more restrictive

typologies, such as Af1, Am4, and Aw5, characterized by high humidity extremes or greater seasonal variation.

These trends are further elucidated in the right panel of the figure, which presents the factorial biplot derived from Principal Component Analysis (PCA), a multivariate method. The first four factors jointly explained 89.7% of the total variance, with Factor 1 (59.1%) representing the dominant climatic gradient (Figure 4a). Species such as *S. macrophylla* (H), *C. multijuga* (H), *V. surinamensis* (H), and *C. goeldiana* (H) are positioned near Af2, Am3, and Aw4, reinforcing their affinity for humid conditions with low climatic seasonality. In contrast, *D. excelsa* (L) and *J. copaia* (L) are associated with Af1 and Aw5, suggesting reduced adaptability to either super-humid or strongly seasonal climates. Intermediate species, including *B. guianensis* (M), *S. amara* (M), and *H. albus* (M), show broader distributions, occupying transitional climatic zones such as Am2 and Aw4, indicative of greater ecological plasticity.

Factor 4 (Figure 4c), despite explaining a smaller portion of the variance (6.2%), revealed specific adaptive patterns under hydric stress. For instance, *S. parahyba* var. *amazonicum* (L) and *S. amara* (M) are associated with Am4, a typology that includes a distinct dry month and annual precipitation ranging from 1500 mm to 2000 mm. The alignment between spatial patterns observed in the typology map and the multivariate groupings in the biplot confirms the robustness of the topoclimatic potential classifications. By integrating climatic zoning with ecological response patterns, this figure consolidates the methodological approach proposed by [11] and reinforces its practical application as a strategic tool for ecological zoning, species selection, and climate-adapted forest restoration across the Amazon. Figure 4 integrates the results of Principal Component Analysis (PCA) applied to twelve native forest species of the Brazilian Amazon, highlighting their associations with climatic typologies and topoclimatic potential classes (high, medium, and low). The PCA revealed that climatic typologies play a central role in structuring the ecological distribution of these species, with the first four components explaining 89.7% of the total variance—Factor 1 alone accounts for 59.1% as the main environmental axis.

Figure 5 displays a matrix of associations between forest species and topoclimatic zones, organized according to established climatic typologies. Each cell in the matrix is represented by a proportional circle, where the color indicates the predominance of species occurrence—ranging from light green/blue (lowest predominance, 0.2) to purple (highest predominance, 1), with intermediate gradients of yellow, orange, and red (0.4, 0.6, 0.8, respectively). Concomitantly, the circle size reflects the absolute area occupied by the species within a given topoclimatic zone, facilitating the simultaneous analysis of both relative representativeness and spatial magnitude.

Dendrograms positioned along the top and left margins of the matrix group the topoclimatic zones and forest species, respectively, based on ecological similarity, allowing for the identification of structural patterns. These hierarchical clusters reveal affinities among species in relation to environmental conditions and allow inferences regarding varying levels of ecological adaptability to the analyzed climatic typologies.

Within this framework, species exhibiting high predominance, evidenced by purple and red circles (e.g., *S. macrophylla*, *C. multijuga*, *H. serratifolius*), are largely associated with Af3 and Am3 typologies, reflecting their ecological preferences for humid and climatically stable environments. Conversely, species with lower predominance, shown by light green/blue and yellow circles (e.g., *D. excelsa* and *J. copaia*), are primarily linked to typologies like Af1, Am4, and Aw5, which represent more extreme or seasonal moisture regimes. Medium predominance species tend to occupy transitional typologies such as Am2 and Aw4, indicating greater ecological plasticity.

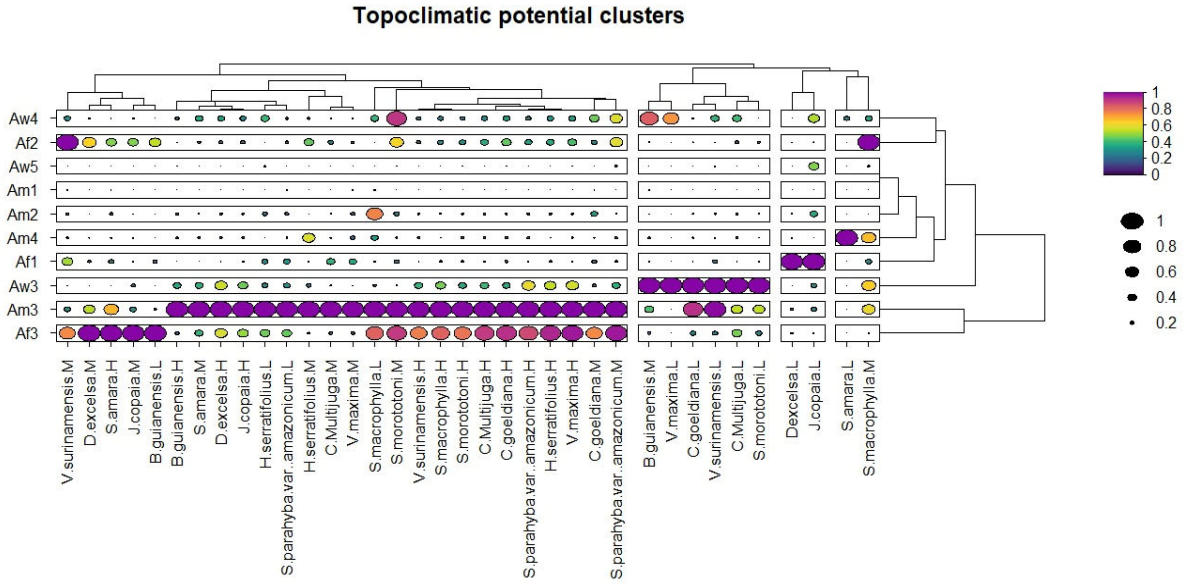


Figure 5. Topoclimatic zoning matrix of twelve native forest species in Brazilian Amazon, showing occurrence intensity across climatic typologies and ecological similarity revealed by hierarchical clustering dendrograms.

This integrated analysis, combining color intensity, bubble size, and clustering patterns, provides key insights into species distribution and confirms the robustness of the derived ecological gradients shaped by climatic typologies. The recognition of species with broad distributions, those with more restricted occurrences, and zones with a higher recurrence of favorable conditions for forest development is thus enabled, underpinning their potential for silvicultural actions.

This multivariate approach not only validates the classification of topoclimatic potential but also provides a reliable scientific foundation for selecting species in ecological restoration initiatives. Particularly in anthropized Amazonian landscapes, where environmental variation and land-use pressures are intense, such detailed climate–species relationships serve as essential tools for planning reforestation, sustainable forest management, and adaptive conservation. The results reinforce the methodological framework proposed by [11], demonstrating its broad applicability beyond the Amazon and into any region where aligning species traits with climatic patterns is crucial to restoration success (Figure 5).

The sensitivity of the Amazon rainforest to changes in rainfall regimes, as highlighted by [26], reveals a non-linear yet reversible relationship between Aboveground Biomass (AGB) and Mean Annual Precipitation (MAP). Their findings suggest a critical MAP threshold, below which vegetation biomass decline accelerates with decreasing rainfall. Notably, these critical thresholds vary geographically across the Amazon, with precipitation seasonality and potential evapotranspiration (PET) identified as key determinants. Their conclusion regarding the potential for forest degradation due to hydrological cycle alterations, particularly the vulnerability of currently water-rich regions to future drought, provides a crucial backdrop for interpreting the species-specific responses observed in our topoclimatic zoning.

Our results, which indicate varying degrees of topoclimatic plasticity among the twelve native species analyzed, align with this understanding of differential vulnerability. Species exhibiting broader high-potential zones across diverse topoclimatic conditions suggest a greater inherent resilience to environmental fluctuations. In this context, the integration of topoclimatic zoning with ecosystem service strategies becomes evident, as observed in urban studies such as [27], where root biomass allocation played a key role

in carbon sequestration under compacted and hydrologically restricted soils. Conversely, species with more restricted high-potential areas may be more susceptible to the predicted shifts in precipitation patterns, underscoring the importance of targeted conservation and management strategies based on their specific topoclimatic requirements.

According to [28], carbon is one of the most relevant climate regulation services provided by native Amazonian species, such as Bertholletia excelsa, particularly in regions undergoing ecological transition or subject to land-use intensification. This reinforces the importance of integrating species-specific ecological functions with topoclimatic suitability models to support multifunctional landscape planning.

The application of multivariate statistical methods, such as Principal Component Analysis (PCA) and cluster analysis, is paramount in topoclimatic zoning studies. These methods are essential for delineating topoclimatic zones, particularly within anthropogenically altered areas of the Brazilian Amazon, as demonstrated in [23]. This aligns with the methodological robustness highlighted by [29] and is further supported by [30], who applied PCA to effectively manage climatic datasets and assess regional vulnerability in coastal Bangladesh. This synergistic combination allows for a more nuanced and statistically grounded identification of homogeneous topoclimatic regions, enhancing the understanding of local climate variation [19].

In the Brazilian Amazon, the climatic typologies previously characterized in our results, consistent with [18] and further elaborated by [11], identify regions with marked seasonal rainfall limitations. These areas require prioritized attention in forest restoration planning due to their increased environmental vulnerability. Ecological transition zones between the Amazon and Cerrado biomes are especially sensitive and are projected to suffer significant biodiversity losses because of ongoing climate change [31]. Studies on tree species composition indicate that the most severe threats to biodiversity conservation are concentrated in these transitional forest ecosystems [32]. Therefore, identifying and mapping suitable areas for native Amazonian species based on topoclimatic criteria is essential to guide conservation and restoration strategies, particularly in landscapes facing intense anthropogenic pressure.

The use of species selected according to their topoclimatic suitability is critical to ensure the success of conservation and reforestation actions. In the southern Amazon, species have undergone long-term adaptive processes, enabling them to survive in marginal conditions distinct from their original habitats. These processes have generated unique patterns of species richness [33] and increased floristic dissimilarity between transitional and core areas of adjacent biomes [34]. The biogeographic gradients formed by rare species in such zones suggest a heightened regional conservation responsibility and reflect evolutionary adaptations shaped by paleoclimatic events [35]. As such, conservation policies should consider these gradients in tandem with topoclimatic distribution patterns to enhance the ecological representativeness and effectiveness of forest recovery initiatives.

Recent studies have emphasized that overlooking the ecological potential of native species can significantly undermine ecosystem resilience. Ref. [36] estimated that biodiversity loss in disturbed tropical forests could double when ecological compatibility is not considered in restoration. Remote sensing studies by [37] have contributed valuable data by linking forest stand parameters with spectral responses from Landsat TM imagery in the Amazon Basin, improving forest monitoring and planning. Ref. [38] also provided critical insight into the hydrological limitations of low-intensity restoration, showing that such efforts may not increase surface water yield, which highlights the need for tailored, context-specific ecological interventions.

Moreover, a broader integrative approach is needed. As indicated by [28], biodiversity and ecosystem services must be analyzed in conjunction within strategic policy frameworks.

These findings reinforce the importance of incorporating multiple scientific perspectives to strengthen forest restoration strategies in the Amazon. The observed patterns of topoclimatic plasticity among native species further justify the integration of species-specific resilience and functional traits into spatial ecological planning. In this context, ecological transitions and their associated environmental services are consistent with broader spatial structures, such as the morphoclimatic domains described by [39], which provide a foundational understanding of the biophysical organization of Brazilian landscapes. The integration of topoclimatic zoning into these domains has the potential to support the design of multifunctional landscapes and regionally effective restoration strategies across the Amazon.

4. Conclusions

This study presents a significant scientific advancement in topoclimatic zoning for native forest species in the Brazilian Amazon, directly contributing to the design of more sustainable silvicultural strategies and enhancing forest resilience amidst climate change. Through our validated zoning model, we precisely characterized the ecological aptitudes of twelve key Amazonian species, a critical step for evidence-based decision-making.

Our findings reveal a clear differentiation in species' adaptation to topoclimatic conditions. Species such as *Dinizia excelsa* (81% occurrence in high potential zones), *Handroanthus albus* (78%), and *Jacaranda copaia* (75%) demonstrate strong adaptation to highly favorable topoclimatic conditions. Their high percentages in these zones confirm their robustness and prioritize their use in ecological restoration and forest management interventions, particularly within anthropized landscapes where maximizing productivity and ensuring ecological resilience are paramount.

We identified species exhibiting varying degrees of ecological breadth. *Simarouba amara* (37% high potential) and *Schizolobium parahyba* var. *amazonicum* (46% high potential) display significant occurrences across medium and low potential zones, highlighting their broader distribution and requiring more nuanced climatic considerations for their effective silvicultural application. Furthermore, *Bagassa guianensis* and *Vochysia maxima*, with notable presences in medium potential zones (26% and 27%, respectively), exemplify a valuable adaptability that extends beyond the highest potential areas, broadening the palette of species for diverse restoration and management options. However, their strategic utilization demands robust technical and ecological monitoring to ensure long-term sustainability.

Our multivariate biplot analysis further reinforces these ecological distinctions by explicitly linking species' predominant occurrences to specific climatic typologies (Af3, Am3, Aw4) that are highly correlated with high topoclimatic potential. This precise association between species distribution and independent climatic subtypes provides a mechanistic understanding of their environmental drivers, crucial for predictive modeling and targeted conservation efforts in altered Amazonian areas. The statistical validation using Phi and Cramér's V coefficients confirms the robustness and predictive accuracy of our topoclimatic zoning model, underscoring its reliability as a planning tool.

In essence, this research provides an unprecedented, empirically validated framework for integrating species-specific topoclimatic potential with regional climatic variations. This scientific advancement empowers land managers and policymakers to move beyond generic approaches, enabling the strategic prioritization of species and locations that will maximize ecological performance and ensure the long-term sustainability and climate resilience of Amazonian native forests. By directing interventions to high-potential zones for highly adapted species and applying adaptive strategies in medium/low potential areas with more resilient species, our findings directly contribute to proactive climate adaptation goals and biodiversity conservation in this vital biome.

Author Contributions: Conceptualization and methodology: L.G.M.; geomatic analysis: L.S.S.L.; climatic data 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., L.S.S.L. and T.M.S.; literature review and geographic coordinate identification: D.L.C. and K.R.d.S.M.; search for occurrences in herbaria 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.

Funding: This research received no external funding. The APC was funded by the authors.

Data Availability Statement: Data sharing is not applicable to this article as no new data were created and analyzed in this study.

Acknowledgments: We would like to express our sincere gratitude to Embrapa for the opportunity to consolidate this multidisciplinary team in the development and application of the TopZon methodology. We are deeply thankful to the Research and Development Program on Native Species Silviculture of Brazil, through the Scientific and Technological Park of Southern Bahia, for their visionary support and trust in the advancement of the topoclimatic zoning of native species in the Amazon.

Conflicts of Interest: Author José Reinaldo da Silva Cabral de Moraes is employed by the company Sombrero Insurance. However, his participation in scientific research projects is fully supported and encouraged by the company, as it brings valuable knowledge and innovation to its activities. The author declares that this study was conducted independently and did not interfere with or compromise his professional responsibilities. There are no commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Heinrich, V.H.A.; Dalagnol, R.; Cassol, H.L.G.; Rosan, T.M.; De Almeida, C.T.; Silva Junior, C.H.L.; Campanharo, W.A.; House, J.I.; Sitch, S.; Hales, T.C.; et al. Large Carbon Sink Potential of Secondary Forests in the Brazilian Amazon to Mitigate Climate Change. *Nat. Commun.* **2021**, *12*, 1785. [CrossRef] [PubMed]
2. Gatti Domingues, L.; Vanni Gatti, L.; Aquino, A.; Sánchez, A.; Correia, C.; Gloor, M.; Peters, W.; Miller, J.; Turnbull, J.; Santana, R.; et al. A New Background Method for Greenhouse Gases Flux Calculation Based in Back-Trajectories Over the Amazon. *Atmosphere* **2020**, *11*, 734. [CrossRef]
3. Lohbeck, M.; Poorter, L.; Martínez-Ramos, M.; Bongers, F. Biomass Is the Main Driver of Changes in Ecosystem Process Rates during Tropical Forest Succession. *Ecology* **2015**, *96*, 1242–1252. [CrossRef] [PubMed]
4. Anderson, J.T.; Song, B. Plant Adaptation to Climate Change—Where Are We? *J. Sytematics Evol.* **2020**, *58*, 533–545. [CrossRef]
5. Li, X.; Ning, Z.; Yang, H. A review of the relationship between China's key forestry ecology projects and carbon market under carbon neutrality. *Trees For. People* **2022**, *9*, 100311. [CrossRef]
6. Souza, L.V.; De Jesus Dos Santos, L.; Ferreira, L.P.; Da Silva Araujo, E.; Lorenço, M.S.; Vieira, S.B.; Sales, A.; Siviero, M.A.; Rosário, B.B.; Da Silva Mota, G.; et al. Potential of the Stem Bark of Bagassa Guianensis Aubl. from Sustainable Forest Management in the Brazilian Amazon as a Raw Material for Biorefineries. *Ind. Crops Prod.* **2025**, *227*, 120754. [CrossRef]
7. Sharma, A.; Tracy, J.; Panwar, P. Ecological Restoration of Degraded Forests for Achieving Land Degradation Neutrality. In *Land Degradation Neutrality: Achieving SDG 15 by Forest Management*; Panwar, P., Shukla, G., Bhat, J.A., Chakravarty, S., Eds.; Springer Nature Singapore: Singapore, 2022; pp. 191–204. ISBN 978-981-19-5477-1.
8. Barbosa, A.P.; Campos, M.A.A.; Sampaio, P.D.T.B.; Nakamura, S.; Gonçalves, C.D.Q.B. O Crescimento de Duas Espécies Florestais Pioneiras, Pau-de-Balsa (Ochroma Lagopus Sw.) e Caroba (Jacaranda Copaia D. Don), Usadas Para Recuperação de Áreas Degradadas Pela Agricultura Na Amazônia Central, Brasil. *Acta Amaz.* **2003**, *33*, 447–482. [CrossRef]
9. Maués, M.M.; de Oliveira, P.E.A.M.; Kanashiro, M. Pollination Biology in Jacaranda Copaia (Aubl.) D. Don. (Bignoniaceae) at the "Floresta Nacional Do Tapajós", Central Amazon, Brazil. *Braz. J. Bot.* **2008**, *31*, 517–527. [CrossRef]
10. Melo, R.R.; Del Menezzi, C.H.S.; Souza, M.R.; Stangerlin, D.M. Avaliação Das Propriedades Físicas, Químicas, Mecânicas e de Superfície de Lâminas de Paricá (*Schizolobium amazonicum* Huber Ex. Ducke). *FLORAM* **2013**, *20*, 238–249. [CrossRef]
11. Martorano, L.G.; Junior, S.B.; Lisboa, L.S.S.; De Moraes, J.R.D.S.C.; Oliveira Aparecido, L.E.D.; Dias, C.T.D.S. A Methodological Proposal for Topoclimatic Zoning of Native Forest Species in the Brazilian Amazon. *Theor. Appl. Climatol.* **2025**, *156*, 249. [CrossRef]
12. Hincks, S.; Carter, J.; Connelly, A. A New Typology of Climate Change Risk for European Cities and Regions: Principles and Applications. *Glob. Environ. Change* **2023**, *83*, 102767. [CrossRef]

13. Audebert, P.; Milne, E.; Schiettecatte, L.-S.; Dionisio, D.; Sinitambirivoutin, M.; Pais, C.; Proença, C.; Bernoux, M. Ecological Zoning for Climate Policy and Global Change Studies. *Nat. Sustain.* **2024**, *7*, 1294–1303. [CrossRef]
14. Mendonça, D.E.; Onofre, S.B. Atividade Antimicrobiana Do Óleo-Resina Produzido Pela Copaiba—Copaifera Multijuga Hayne (Leguminosae). *Rev. Bras. Farmacogn.* **2009**, *19*, 577–581. [CrossRef]
15. Miranda, K.; Amaral Neto, M.; Sousa, R.; Coelho, R. Manejo Florestal Sustentável Em Unidades de Conservação de Uso Comunitário Na Amazônia. *Soc. Nat.* **2020**, *32*, 778–792. [CrossRef]
16. Xavier, A.C.; Scanlon, B.R.; King, C.W.; Alves, A.I. New improved Brazilian daily weather gridded data (1961–2020). *Int. J. Climatol.* **2022**, *42*, 8390–8404. [CrossRef]
17. Xavier, A.C.; Kingsmill, N.; Schaefer, C.E.G.R.; Cunha, A.P.M. Brazilian Daily Weather Gridded Data (BR-DWGD): Daily Meteorological Data Set for Brazil. *Sci. Data* **2022**, *9*, 1.
18. Martorano, L.C.; Nechet, D.; Pereira, L.G. Tipologia Climática Do Estado Do Pará: Adaptação Do Método de Köppen. *Bol. Geogr. Teorética* **1993**, *23*, 307–312.
19. Martorano, L.G.; Junior, S.B.; De Moraes, J.R.D.S.C.; Lisboa, L.S.S.; Nascimento, W.; Correa, D.L.; Santos, T.M.; Lima, R.F.D.; Magalhães, K.R.D.S.; Dias, C.T.D.S. Topoclimatic Zoning of Three Native Amazonian Forest Species: Approach to Sustainable Silviculture. *Sustainability* **2025**, *17*, 1366. [CrossRef]
20. Instituto Brasileiro de Geografia e Estatística. Banco de Dados de Informações Ambientais (BDiA). IBGE. 2024. Available online: https://bdiaweb.ibge.gov.br/ (accessed on 10 December 2024).
21. Departamento Nacional de Produção Mineral, Ministério das Minas e Energia, Brasil. *Projeto RADAMBRASIL: Levantamento de Recursos Naturais: Folha SA.22 Belém: Geologia, Geomorfologia, Pedologia, Vegetação e Uso Potencial da Terra*; MME-DNPM: Rio de Janeiro, Brazil, 1983; Volume 5.
22. Venturieri, A.; da Costa, M.R.; Oliveira, R.P. Zoneamento Ecológico-Econômico da Amazônia Legal: Documento Síntese Para Apoio à Gestão Territorial Sustentável. Embrapa Amazônia Oriental. 2016. Available online: https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1060135 (accessed on 10 December 2024).
23. Martorano, L.G.; Tourne, D.C.M.; Lisboa, L.S.; de Sousa, V.G.; dos Santos, L.S.; Brienza Júnior, S. *Zoneamento Topoclimático do Taxi-Branco (Tachigali vulgaris L.F.) na Amazônia Legal: Estratégias de Planejamento com Metas de Desenvolvimento Sustentável*; Série Documentos, No. 435; Embrapa Amazônia Oriental: Belém, Brazil, 2018.
24. Tourne, D.C.; Martorano, L.G.; Junior, S.B.; Dias, C.T.D.S.; Lisboa, L.S.; Sartorio, S.D.; Vettorazzi, C.A. Potential topoclimatic zones as support for forest plantation in the Amazon: Advances and challenges to growing Paricá (Schizolobium amazonicum). *Environ. Dev.* **2016**, *18*, 26–35. [CrossRef]
25. Martorano, L.G.; Siviero, M.A.; Tourne, D.C.M.; Vieira, S.B.; Fitzjarrald, D.R.; Vettorazzi, C.A.; Brienza Júnior, S.; Yeared, J.A.G.; Meyering, É.; Lisboa, L.S.S. Agriculture and forest: A sustainable strategy in the Brazilian Amazon. *Aust. J. Crop Sci.* **2016**, *10*, 1136–1143. [CrossRef]
26. Nian, D.; Bathiany, S.; Sakschewski, B.; Drüke, M.; Blaschke, L.; Ben-Yami, M.; Von Bloh, W.; Boers, N. Rainfall Seasonality Dominates Critical Precipitation Threshold for the Amazon Forest in the LPJmL Vegetation Model. *Sci. Total Environ.* **2024**, *947*, 174378. [CrossRef] [PubMed]
27. Yoon, T.K.; Lee, S.; Lee, S.; Lee, J.-M.; Son, Y.; Lee, S. Root Biomass Allocation and Carbon Sequestration in Urban Landscaping Tree Species in South Korea. *Forests* **2024**, *15*, 2104. [CrossRef]
28. Martorano, L.G.; Guedes, M.C.; Lisboa, L.S.; da Silva Cabral de Moraes, J.R.; do Nascimento, N.C.C.; de Paiva Salomão, R.; Martorano, P.G.; de Oliveira Aparecido, L.E.; Tourne, D.C.M.; dos Santos Dias, C.T.; et al. Condições topoclimáticas e serviços ecossistêmicos prestados pelas castanheiras no Bioma Amazônia. In *Castanha-da-Amazônia: Estudos Sobre a Espécie e Sua Cadeia de Valor*; Aspectos sociais, econômicos e organizacionais; Embrapa: Brasília, Brazil, 2023; Volume 1.
29. Vicente-Serrano, S.M.; El Kenawy, A.; Azorin-Molina, C.; Chura, O.; Trujillo, F.; Aguilar, E.; Martín-Hernández, N.; López-Moreno, J.I.; Sanchez-Lorenzo, A.; Moran-Tejeda, E.; et al. Average Monthly and Annual Climate Maps for Bolivia. *J. Maps* **2016**, *12*, 295–310. [CrossRef]
30. Uddin, M.N.; Saiful Islam, A.K.M.; Bala, S.K.; Islam, G.M.T.; Adhikary, S.; Saha, D.; Haque, S.; Fahad, M.G.R.; Akter, R. Mapping of Climate Vulnerability of the Coastal Region of Bangladesh Using Principal Component Analysis. *Appl. Geogr.* **2019**, *102*, 47–57. [CrossRef]
31. Maciel, E.A.; Oliveira-Filho, A.T.; Sobral-Souza, T.S.; Marimon, B.S.; Cupertino-Eisenlohr, M.A.; José-Silva, L.; Eisenlohr, P.V. Climate Change Forecasts Suggest That the Conservation Area Network in the Cerrado-Amazon Transition Zone Needs to Be Expanded. *Acta Oecologica* **2021**, *112*, 103764. [CrossRef]
32. Dos Santos, K.; Kinoshita, L.S.; Santos, F.A.M.D. Tree Species Composition and Similarity in Semideciduous Forest Fragments of Southeastern Brazil. *Biol. Conserv.* **2007**, *135*, 268–277. [CrossRef]
33. Higuchi, P.; da Silva, A.C.; Ferreira, T.S.; de Souza, S.T.; Gomes, J.P.; da Silva, K.M.; dos Santos, K.F. Floristic composition and phytogeography of the tree component of Araucaria Forest fragments in southern Brazil. *Braz. J. Bot.* **2012**, *35*, 145–157. [CrossRef]

34. Pärtel, M.; Bruun, H.H.; Sammul, M. Biodiversity in Temperate European Grasslands: Origin and Conservation. *Grassl. Sci. Eur.* **2005**, *10*, 1–14.
35. Barlow, J.; Lennox, G.D.; Ferreira, J.; Berenguer, E.; Lees, A.C.; Nally, R.M.; Thomson, J.R.; de Barros Ferraz, S.F.; Louzada, J.; Oliveira, V.H.F.; et al. Anthropogenic Disturbance in Tropical Forests Can Double Biodiversity Loss from Deforestation. *Nature* **2016**, *535*, 144–147. [CrossRef]
36. Lu, D.; Mausel, P.; Brondízio, E.; Moran, E. Relationships between Forest Stand Parameters and Landsat TM Spectral Responses in the Brazilian Amazon Basin. *For. Ecol. Manag.* **2004**, *198*, 149–167. [CrossRef]
37. Mataveli, G.A.V.; Pereira, G.; De Oliveira, G.; Seixas, H.T.; Cardozo, F.D.S.; Shimabukuro, Y.E.; Kawakubo, F.S.; Brunsell, N.A. 2020 Pantanal's Widespread Fire: Short- and Long-Term Implications for Biodiversity and Conservation. *Biodivers Conserv.* **2021**, *30*, 3299–3303. [CrossRef] [PubMed]
38. Dib, V.; Nalon, M.A.; Amazonas, N.T.; Vidal, C.Y.; Ortiz-Rodríguez, I.A.; Daněk, J.; Gomes, T.F. Drivers of change in biodiversity and ecosystem services in the Cantareira System Environmental Protection Area: A prospective analysis of public policy implementation. *Biota Neotrop.* **2020**, *20* (Suppl. S1), e20190915. [CrossRef]
39. Ab'Sáber, A.N. *Os Domínios de Natureza No Brasil: Potencialidades Paisagísticas*; Ateliê Editorial: Los Angeles, CA, USA, 2003; Volume 1, ISBN 85-7480-099-6.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.