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Variability in Fruit Production of Carapa Guianensis Associated with Edaphoclimatic Factors in the Amazon

Carlos Darwin Angulo Villacorta [1,2,*], Denilson Silva da Conceição [3], Rodolfo Juan Chuchon Remon [4], Donald Manigat [5], Lorena Antunes Jimenez [5] and José Julio de Toledo [1,5]

[1] Programa de Pós-graduação em Biodiversidade Tropical, Universidade Federal do Amapá UNIFAP´, Macapá, AP, Brazil
[2] Dirección de Investigación en Manejo Integral de Bosques y Servicios Ecosistémicos. Instituto de Investigaciones de la Amazonía Peruana (IIAP), San Martín, Perú
[3] Programa de Pós-Graduação em Ciências Ambientais, Universidade Federal do Amapá-AP, Brasil
[4] Dirección de Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA). Estación Experimental Agraria El Porvenir, Juan Guerra, Perú
[5] Centro Avançado de Pesquisa-Ação da Conservação e Recuperação Ecossistêmica da Amazônia – CAPACREAM. Universidade Federal do Amapá – UNIFAP, Macapá, AP, Brasil
* Correspondence: cangulovillacorta@gmail.com

Abstract

Carapa guianensis Aubl., widely distributed throughout the Amazon, is recognized for its ecological, economic, and social importance, and constitutes a key source of income for numerous extractive communities. However, fruit production exhibits marked spatial variation that may be influenced by soil properties and climatic factors. In this study, we assessed this variability using data from 21 studies conducted in the Brazilian Amazon, incorporating georeferenced information from each site on climate and soil characteristics. Environmental variables were evaluated using Random Forest models. Average fruit productivity showed a broad range (0.34 to 34.6 kg·tree^{-1}·year^{-1}), with higher values in várzea forests (16.5 kg·tree^{-1}·year^{-1}) and lower values in igapó forests (2.5 kg·tree^{-1}·year^{-1}). The model explained 42% of the observed variability ($R^2 = 0.83$ in cross-validation), identifying soil organic carbon, mean annual temperature, and clay content as the most influential predictors. These findings demonstrate that fruit production is shaped by the interaction between edaphic and climatic conditions, which determine the species' productivity patterns, and highlight the need to foster adaptive management strategies that ensure the sustainable use of andiroba across Amazonian ecosystems.

Keywords: *Carapa guianensis*; Amazon; edaphoclimatic factors; fruit production; Random Forest; sustainable forest management

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1. Introduction

The Amazon region contains some of the most biodiverse ecosystems on the planet and is characterized by a remarkable variety of tree species [39,47], many of which hold significant ecological, economic, and social importance [14,55]. Among these is *Carapa guianensis* Aubl. (Meliaceae), commonly known as andiroba, a large tree widely distributed throughout the Amazon basin [35] and noted for its multiple uses [52]. Its seeds are primarily used for oil extraction [12], which has medicinal [9,34,38,57,61], cosmetic [10], and insecticidal properties [11], making it an important source of income for traditional Amazonian communities [46]. The species is also valued for timber [24,29] and possesses relevant cultural significance. Moreover, its presence plays a fundamental role in maintaining ecosystem services, including nutrient cycling and the provision of food resources for wildlife [46].

Fruit production in *C. guianensis* exhibits considerable temporal and spatial variability, likely influenced by different environmental factors [30] that can determine its annual yield [43]. Several studies have indicated that the productivity of tropical forest species is closely linked to edaphoclimatic conditions, including precipitation, temperature, and soil properties [13,32,37]. For *C. guianensis*, fluctuations in annual fruit production have been reported across various regions of the Amazon, suggesting a response to seasonal climatic variation and to extreme events such as prolonged droughts or atypical floods [26,53]. This variability is common among tropical tree species and may represent an adaptive strategy, although it also poses challenges for management aimed at the sustainable harvest of fruits. Despite the existence of long-term data records, analyses capable of identifying fruit production patterns associated with edaphoclimatic factors across the entire Amazon are still lacking.

Precipitation plays a fundamental role in the phenology and fruit production of Amazonian species [13,54]. Changes in hydrological patterns can directly affect processes such as flowering, pollination, and fruit development [31]. Various studies highlight that the alignment between phenological events and the availability of water and nutrients largely determines the reproductive success of tree species, leading to substantial interannual variability in fruiting [24,26,50,51]. In addition to precipitation, soil properties such as fertility, texture, effective depth, and nutrient availability also influence the vegetative and reproductive growth of tropical trees [5,41]. The interplay between climatic and edaphic conditions, together with intraspecific genetic variation, contributes to the heterogeneous productivity patterns observed across different regions of the Amazon.

An additional aspect for understanding productivity patterns is the diversity of environmental conditions found across the Amazon. The region is composed of a mosaic of ecosystems that differ widely in their flooding regimes, nutrient availability, and hydrological dynamics [23]. In várzea areas, which are periodically flooded, trees receive a constant supply of nutrient-rich sediments, which supports higher productivity [33,60]. In contrast, terra firme forests, where flooding does not occur, develop on nutrient-poor soils that restrict both growth and reproduction in many species [21]. Baixio environments, characterized by waterlogged soils and generally low fertility, present intermediate and highly variable conditions. On the other hand, igapó forests—flooded by acidic blackwater and with very limited nutrient availability—represent some of the most restrictive environments for fruit production [8,59,60]. In this context, assessing fruit production in *C. guianensis* across these distinct Amazonian environments is essential for understanding how environmental heterogeneity shapes the species' phenological and reproductive patterns.

The interaction between edaphic and climatic factors within each of these environments exerts a strong influence on the reproduction of *C. guianensis* [25,29]. In várzea forests, the annual deposition of sediments during flooding increases soil fertility [15], which can enhance vegetative growth and, consequently, fruit production. In contrast, in terra firme forests, highly weathered and nutrient-poor soils impose nutritional limitations, making water availability and nutrient cycling critical elements for reproductive phenology. In baixio environments, prolonged soil saturation can reduce root aeration and limit fruit production, while in igapó forests, the low fertility associated with acidic blackwater [21,60] represents one of the most restrictive contexts for fruiting. These edaphoclimatic conditions, combined with interannual variability in precipitation and the occurrence of extreme climatic events, generate highly heterogeneous patterns of fruit production throughout the Amazon [19,49].

In this context, understanding the edaphic and climatic determinants of fruit production in *C. guianensis* is essential for the sustainable management of the species, particularly in initiatives focused on non-timber forest products and forest conservation. Beyond strengthening the scientific basis for community-based management, this knowledge can guide public policies and conservation strategies that reconcile local income generation with biodiversity preservation. However, quantitative studies that integrate environmental variables with actual fruit production remain scarce in the Amazonian literature, limiting the understanding of causal relationships and the ability to predict productivity under different conditions.

Therefore, this study seeks to fill this gap by analyzing the variability in fruit production of *C. guianensis* across different localities in the Amazon, relating it to climatic and edaphic factors using empirical data and statistical modeling. By providing scientific evidence on the environmental factors that determine productivity, this research aims to support the development of adaptive management strategies and strengthen sustainable value chains based on the use of andiroba.

2. Materials and Methods

2.1. Literature Review

A literature review was conducted covering scientific publications that reported quantitative data on fruit production of *Carapa guianensis* in the Amazon region between 2000 and 2024. Searches were performed in the Scopus, Web of Science, SciELO, and Google Scholar databases, using combinations of keywords in English, Spanish, and Portuguese (*Carapa guianensis*, fruit production, Amazon, seed yield, andiroba, phenology), linked with Boolean operators (AND/OR). Only studies that provided georeferenced data or allowed precise identification of the sampling site were included.

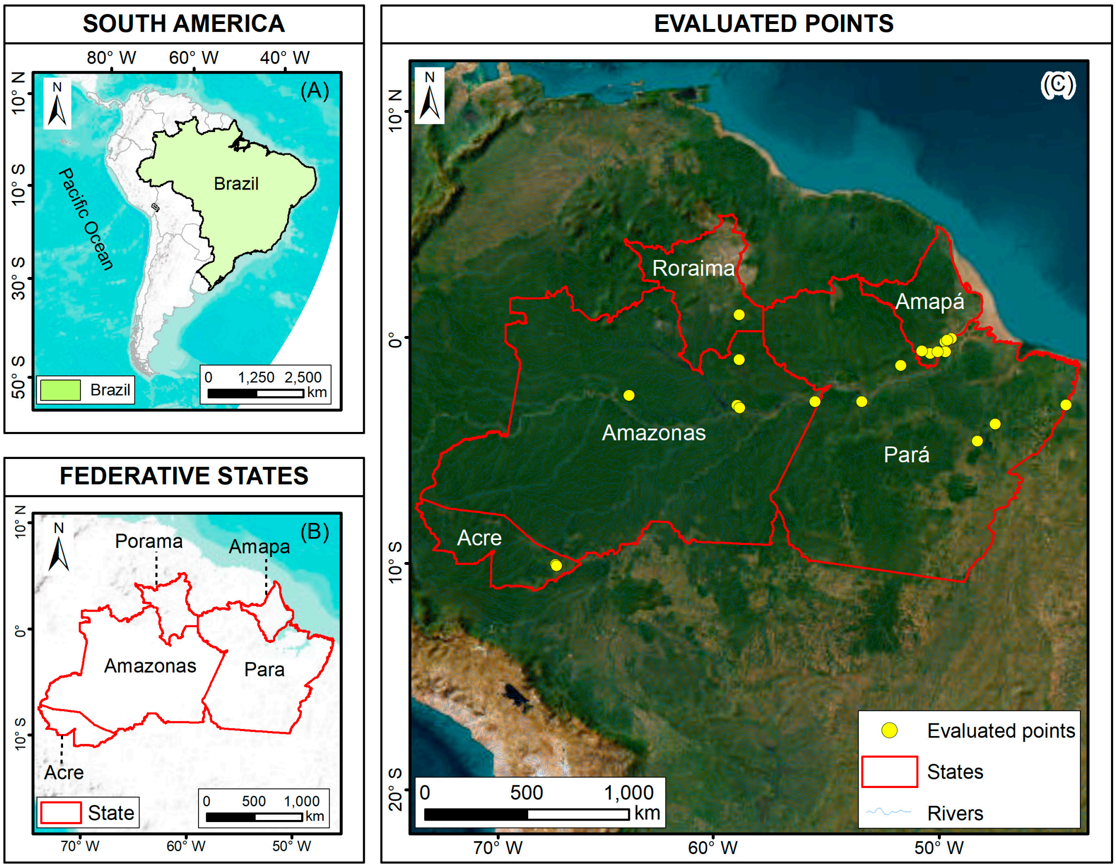

Figure 1. Map of the geographic distribution of studies on the fruit production of Carapa guianensis in the Brazilian Amazon. (A) Location of Brazil within the context of South America. (B) States considered in the analyses. (C) Location points of the areas where studies recorded in the literature were conducted, covering different types of Amazonian ecosystems (terra firme, várzea, among others).

For each selected record, the following information was extracted: total number of fruits or seeds per tree, forest type (terra firme, várzea, baixio, restinga, and igapó), geographic coordinates, and sampling year.

2.2. Acquisition of Fruit Production Data

The average fruit production per tree was obtained from data extracted from scientific articles. In some studies, the authors directly reported the mean annual production per individual (kg tree^{-1} year^{-1}), and these values were used as originally presented. In cases where studies provided tables at the individual-tree level, the data were compiled and the mean annual production was calculated accordingly.

For studies that reported fruit production only in terms of seed weight (kg tree^{-1} year^{-1}), values were converted to their fruit equivalents. To do this, the average weight of a *C. guianensis* seed (0.25 g) was used, which allowed standardizing the estimates in kilograms of fruits per tree per year [16]. This procedure ensured comparability among the different data sources and facilitated the integration of information into a single dataset.

The diameter at breast height (DBH) was considered for each site to evaluate the effect of tree size on mean fruit production whenever this information was available. Of the 21 sites in the database, 13 reported mean DBH values. This methodological decision of partial exclusion aimed to balance spatial coverage by retaining all 21 sites in the general descriptive and predictive analyses, while ensuring rigor by controlling for a dendrometric covariate when appropriate.

The comparison between models fitted to the same dataset (model without DBH vs. model with DBH, both applied to the 13 available observations) was used to assess whether the inclusion of DBH significantly improved model performance, using an F-test (ANOVA for nested models). No DBH imputation procedures were applied to replace missing measurements in other sites in order to avoid introducing assumed dendrometric distributions that could bias ecological inferences.

2.2. Environmental Variables

To evaluate the variability in fruit production of *Carapa guianensis* associated with edaphoclimatic factors, the following variables were considered: (1) mean annual temperature (°C × 10); (2) temperature seasonality, expressed as standard deviation × 100 (°C × 10); (3) precipitation seasonality ((standard deviation / mean) × 100), in %; (4) annual precipitation, in millimeters; and (5) precipitation of the driest quarter, in millimeters. These variables were obtained from the WorldClim global climate database, version 2.1(https://www.worldclim.org/data/index.html), derived from meteorological station records and representing climatic averages for the period 1950–2000 [17]. WorldClim provides high-resolution (~1 km²) interpolated climate data widely used in ecological and biogeographical research.

Soil physicochemical variables were extracted using the specific geographic coordinates of each sampling point. The edaphic variables considered were: (1) organic carbon density (hg m^{-3}); (2) organic carbon stock (t ha^{-1}); (3) bulk density of the fine soil fraction (cg cm^{-3}); (4) clay content (<0.002 mm) in the fine fraction (g kg^{-1}); (5) sand content (>0.05/0.063 mm) in the fine fraction (g kg^{-1}); (6) silt content (≥0.002 and ≤0.05/0.063 mm) in the fine fraction (g kg^{-1}); (7) cation exchange capacity at pH 7 (mmol(c) kg^{-1}); (8) organic carbon content in the fine fraction (dg kg^{-1}); (9) total nitrogen (N) (cg kg^{-1}); and (10) soil pH in H_2O (pH × 10).

These variables were obtained from the SoilGrids 250 m 2.0 database (https://soilgrids.org), which produces global maps of soil properties at an average spatial resolution of 250 m using machine-learning models that generate interpolated estimates of edaphic variables [40]. The ten physicochemical parameters available on the platform were considered, calculated as the mean of three depth intervals (0–5, 5–15, and 15–30 cm), representing the topsoil layer (0–30 cm).

Data were extracted at the specific sampling points defined in the study, retaining the original column names, parameters, and corresponding units. The data download was conducted in September 2025 using JavaScript scripts developed in Google Earth Engine, a geospatial analysis platform that enables processing of large environmental and satellite datasets at a global scale [20].

2.3. Random Forest

For the analysis of environmental and predictive data, the Random Forest (RF) algorithm was used. RF is an automated, decision tree–based method that combines multiple models to improve accuracy and reduce the risk of overfitting [3]. Its operation consists of generating numerous classification or regression trees, each built from random subsets of the training data and predictor variables. The model produces its final output by aggregating the predictions of all trees, using averaging in the case of regression or majority voting in the case of classification.

This method was selected due to its robustness in environmental studies, its ability to handle highly correlated predictors, and its strong performance even when nonlinear relationships exist between explanatory variables and the response variable. RF was used to determine the relative importance of bioclimatic and edaphic variables in explaining the observed variability in fruit production. Analyses were performed in R [42] using the *randomForest* package [27].

The dependent variable used was the mean fruit production of *C. guianensis* (kg tree^{-1} year^{-1}). Predictor variables included soil characteristics such as bulk density (g cm^{-3}), cation exchange capacity (cmol(+) kg^{-1}), clay content (g kg^{-1}), nitrogen content (g kg^{-1}), pH, organic carbon density (kg m^{-3}), sand content (g kg^{-1}), silt content (g kg^{-1}), soil organic carbon (g kg^{-1}), soil organic carbon stock (Mg ha^{-1}), and total texture (clay + sand + silt). Climatic variables included annual precipitation (mm year^{-1}), precipitation of the driest quarter (mm), precipitation seasonality (CV, %), mean annual temperature (°C), and temperature seasonality (standard deviation × 100).

To examine relationships among predictors, a Pearson correlation matrix was constructed to identify significant associations and potential multicollinearity issues. Variables with high correlations ($r > 0.80$) were considered for exclusion from the model. The *mtry* parameter was set to 2, and the model was trained using five-fold cross-validation (5-fold CV). A total of 500 decision trees were generated to ensure stable predictions. Model performance was evaluated using three metrics: mean absolute error (MAE), root mean square error (RMSE), and coefficient of determination (R^2), calculated from the observed and predicted values during cross-validation.

The relative importance of the predictors was estimated using the "Mean Decrease in Accuracy" and "Mean Decrease in Gini" criteria, which allowed ranking the variables with the greatest influence. For those variables with the highest weight in the model, Partial Dependence Plots (PDPs) were generated to visualize their marginal effects on mean fruit production while keeping the remaining variables constant at their average values. Predictive performance was validated using a plot of observed versus predicted values, accompanied by the calculation of the adjusted R^2.

Additional visualizations, such as scatterplots and stripcharts, were produced to compare fruit production across environmental variables and forest types. Multiple linear regression models were also fitted using subsets of predictor variables (soil texture, climatic factors, and soil chemical properties), and multicollinearity was evaluated using the Variance Inflation Factor (VIF). Variables with VIF > 2 were iteratively removed until more parsimonious models were obtained.

All compiled data were organized and systematized into a database, and statistical analyses were conducted in R, version 4.5.0 [42].

3. Results

The study included a total of 21 independent investigations conducted across different states of the Brazilian Amazon (Table 1). Most studies were concentrated in the states of Pará (n = 7), Amapá (n = 5), and Acre (n = 4), followed by Amazonas (n = 2), Roraima (n = 2), and Maranhão (n = 1) (Figure 2).

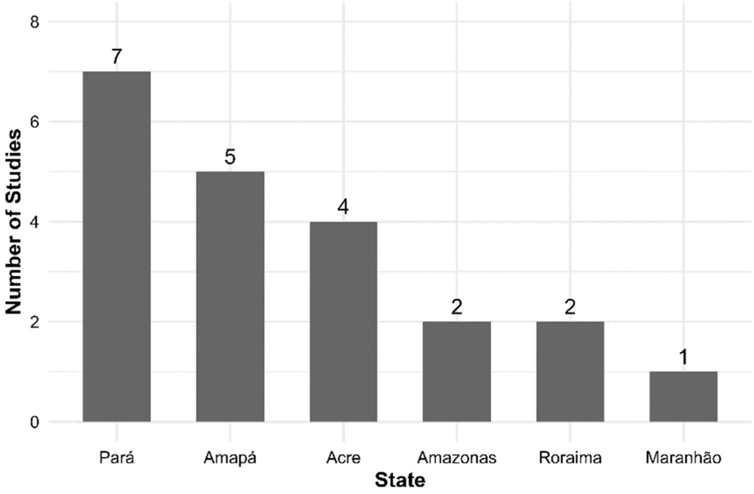

Figure 2. Number of studies on fruit production conducted in different states of the Brazilian Amazon.

The number of sampled trees per study ranged from 6 to 352 individuals, with an average of 98.2 ± 83.6 trees (mean ± standard deviation). The diameter at breast height (DBH) averaged 37.95 ± 12.14 cm, with values ranging from 10.0 to 55.0 cm. Mean fruit production varied between 0.34 kg·tree^{-1}·year^{-1} and 34.6 kg·tree^{-1}·year^{-1}, with an overall mean of 8.30 ± 9.35 kg·tree^{-1}·year^{-1}.

When comparing forest types, the mean DBH was highest in Igapó forests (41.45 ± 5.59 cm), followed by Terra Firme forests (40.16 ± 9.02 cm), and lowest in Várzea forests (33.29 ± 16.39 cm). Regarding fruit production, Várzea forests exhibited the highest mean value (16.55 ± 11.87 kg·tree^{-1}·year^{-1}), followed by Terra Firme forests (7.12 ± 7.47 kg·tree^{-1}·year^{-1}), whereas Igapó forests showed the lowest production (2.52 ± 0.37 kg·tree^{-1}·year^{-1}). For Baixio and Restinga forests, only one study was available for each environment, with mean productions of 1.48 and 4.10 kg·tree^{-1}·year^{-1}, respectively (Figure 3).

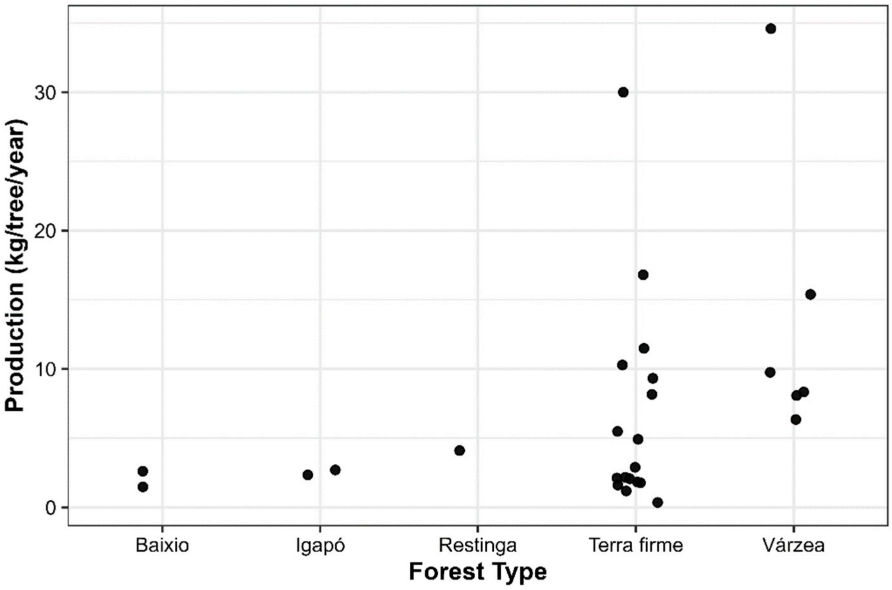

Figure 3. Variation in fruit production of Carapa guianensis (kg·tree^{-1}·year^{-1}) among forest types (Baixio, Igapó, Restinga, Terra firme, and Várzea) in the Amazon.

Author	State	Municipality	Study area	Forest type	Longitude (°)	Latitude (°)	Number of trees	Mean DBH (cm)	Mean fruit production (kg tree^{-1} year^{-1})
Dias (2001)	Pará	Belterra	Floresta Nacional do Tapajós" (FLONA Tapajós)	Terra firme	54°45'0.00"W	2°40'0.12"S	192	41.5	10.29
Dias (2001)	Pará	Belterra	Floresta Nacional do Tapajós" (FLONA Tapajós)	Terra firme	50°0'0.00"W	4°10'0.12"S	137	41.3	9.67
Dias (2001)	Pará	Belterra	Floresta Nacional do Tapajós" (FLONA Tapajós)	Terra firme	54°45'0.00"W	2°40'0.12"S	86	37.4	8.17
Plowden (2004).	Pará	Nova Esperança do Piriá	Aldeia de Tekohaw	Terra firme	46°33'25.30"W	2°37'35.35"S	46	39.4	1.2
Mellinger (2006)	Amazonas	Mara	Reserva de Desenvolvimento Sustentável Amanã	Igapó	64°38'24.00"W	2°31'42.00"S	42	45.4	2.7
Lima (2007)	Acre	Rio Branco	Reserva Florestal da Embrapa Acre	Baixio	67°44'28.00"W	9°58'29.00"S	26	N.A.	1.48
Lima (2007)	Acre	Rio Branco	Reserva Florestal da Embrapa Acre	Terra firme	67°44'28.00"W	9°58'29.00"S	23	N.A.	2.16
Pena (2007)	Pará	Breu_Branco	Empresa Izabel medeiros do Brasil	Terra firme	49°18'31.90"W	3°27'2.80"S	50	44.95	2.12
Wadt et al.(2008)	Acre	Rio Branco	Reserva Florestal da Embrapa Acre	Terra firme	67°44'28.00"W	9°58'29.00"S	118	25	1.6
Guedes et al.(2008)	Amapá	Mazagão	Escola Família Agrícola (EFA) doCarvão	Várzea	51°22'0.00"W	0°10'60.00"S	6	10	15.4
Lima et al.(2009)	Amapá	Macapá	APA da Fazendinha	Várzea	51°7'41.78"W	0°3'10.39"S	30	44.4	34.6
Gomes (2010)	Amapá	Mazagão	Reserva florestal da Empresa Brasileira de Pesquisa Agropecuária	Terra firme	51°58'0.00"W	0°40'0.00"S	34	38.1	4.9
Gomes (2010)	Amapá	Mazagão	Reserva florestal da Empresa_Brasileira de Pesquisa Agropecuária	Várzea	51°58'0.00"W	0°40'0.00"S	12	23.7	6.35
Klimas (2011)	Acre	na	Reserve of the Brazilian Agricultural Research Corporation (EMBRAPA)	Terra firme	67°42'19.00"W	10°1'28.00"S	168	37.5	1.77
Klimas (2011)	Acre	na	Reserve of the Brazilian Agricultural Research Corporation (EMBRAPA)	Igapó	67°42'19.00"W	10°1'28.00"S	184	37.5	2.33
Nascimento (2013)	Amazonas	Parintins	Comunidade N. S. do Rosário	Terra firme	56°41'36.60"W	2°42'38.52"S	15	N.A.	16.8
Pinto (2013)	Amazonas	Manaus	Reserva Florestal Ducke	Terra firme	59°58'59.88"W	2°55'0.12"S	30	N.A.	9.31
Pinto (2013)	Amazonas	Manaus	Reserva Florestal Ducke	Terra firme	59°52'59.88"W	3°1'0.12"S	30	N.A.	9.31
Marques (2012)	Roraima	Sao Joao da Baliza	Área de reserva legal de uma propirdade particular	Várzea	59°54'41.00"W	0°57'2.00"S	73	47.75	9.76
Klimas (2012)	Acre	na	Forest reserve of the Brazilian Agricultural Research Corporation (EMBRAPA)	Terra firme	67°42'19.00"W	10°1'28.00"S	352	32.5	2.06
Barros (2014)	Amapá	Laranjal do Jarí	Reserva Extrativista Rio Cajari (RESEX) Cajari)	Terra firme	52°18'19.01"W	0°33'42.98"S	62	N.A.	1.84
Barros (2014)	Amapá	Mazagão	Estação Experimental da Embrapa	Várzea	51°17'20.00"W	0°6'54.00"S	16	N.A.	8.09
da Silva (2015)	Amapá	Mazagão	Campo_Experimental_do_Mazagão_da_Embrapa	Várzea	51°17'20.00"W	0°6'54.00"S	16	30	8.35
Martins (2016)	Pará	Almeirim	Cafezal /Paru	Terra firme	53°9'34.85"W	1°9'55.76"S	20	40.7	2.9
Tonini (2017)	Roraima	São João da Baliza		Terra firme	59°54'41.00"W	0°57'2.00"S	121	20	29.99
Londres (2017)	Pará	Gurupá	Reserva de desemvolvimento Sustentavel (RDS) Itatupã-Baquiá	Terra firme	51°21'35.64"W	0°34'48.36"S	67	55	5.5
Londres (2017)	Pará	Gurupá	Reserva de desemvolvimento Sustentavel (RDS) Itatupã-Baquiá	Baixio	51°21'35.64"W	0°34'48.36"S	120	35	2.6
Londres (2017)	Pará	Gurupá	Reserva de desemvolvimento Sustentavel (RDS) Itatupã-Baquiá	Restinga	51°21'35.64"W	0°34'48.36"S	40	28	4.1
Lourenço et al..(2017)	Pará	Gurupá	Reserva de desemvolvimento Sustentavel (RDS) Itatupã-Baquiá	Terra firme	56°41'36.71"W	2°42'38.53"S	21	55	11.47
Correa et al. (2020)	Amapá	Porto Grande	Projeto de Assentamento Nova Canaã	Terra firme	51°40'20.86"W	0°35'12.16"S	26	N.A.	0.34

Relationship between fruit production and environmental variables

Higher production levels were concentrated in regions with annual precipitation between 2,400 and 2,800 mm, although with substantial variability (Figure 4a). Precipitation during the driest quarter did not show a defined trend; however, the highest production values were distributed between 200 and 300 mm (Figure 4b). Regarding precipitation seasonality, trees tended to produce more when the coefficient of variation ranged between 40% and 50%, with reduced yields outside this interval (Figure 4c). Mean annual temperature (Figure 4d) and temperature seasonality (Figure 4e) did not show clear relationships with fruit production, although the highest fruiting values were concentrated in sites with lower thermal variation.

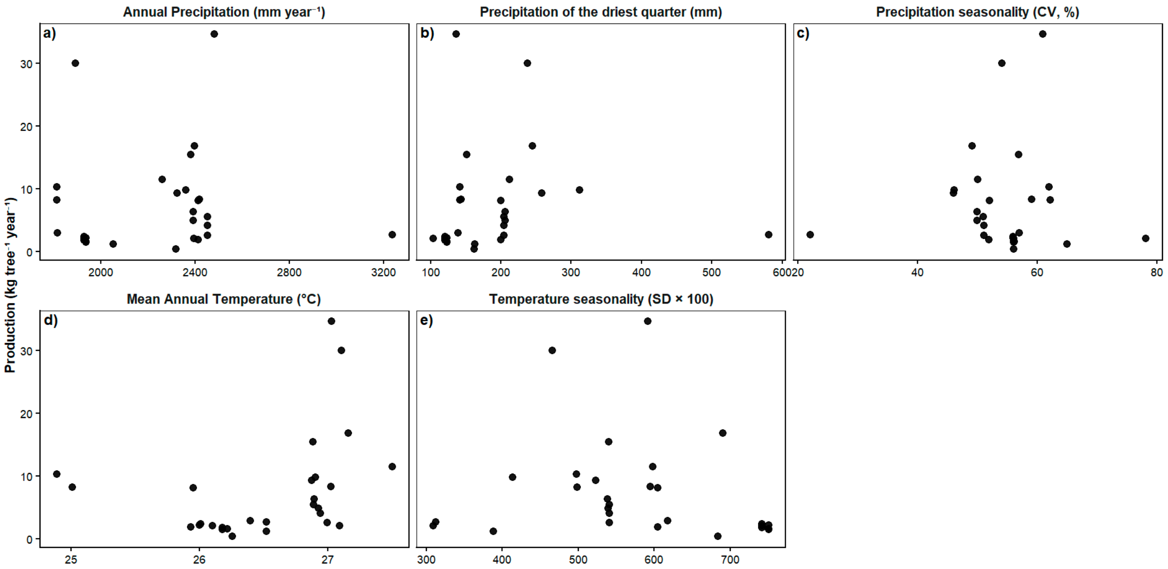

Figure 4. Relationship between fruit production of Carapa guianensis (kg tree⁻¹ year⁻¹) and climatic variables: Annual Precipitation (mm year⁻¹), Precipitation of the Driest Quarter (mm), Precipitation Seasonality (CV, %), Mean Annual Temperature (°C), and Temperature Seasonality (SD × 100).

Regarding soil properties, production was higher in sites with sand content between 30% and 50% (Figure 5), whereas values above 60% were associated with lower yields. In contrast, soils with silt contents ranging from 30% to 40% exhibited the highest production levels (Figure 5).

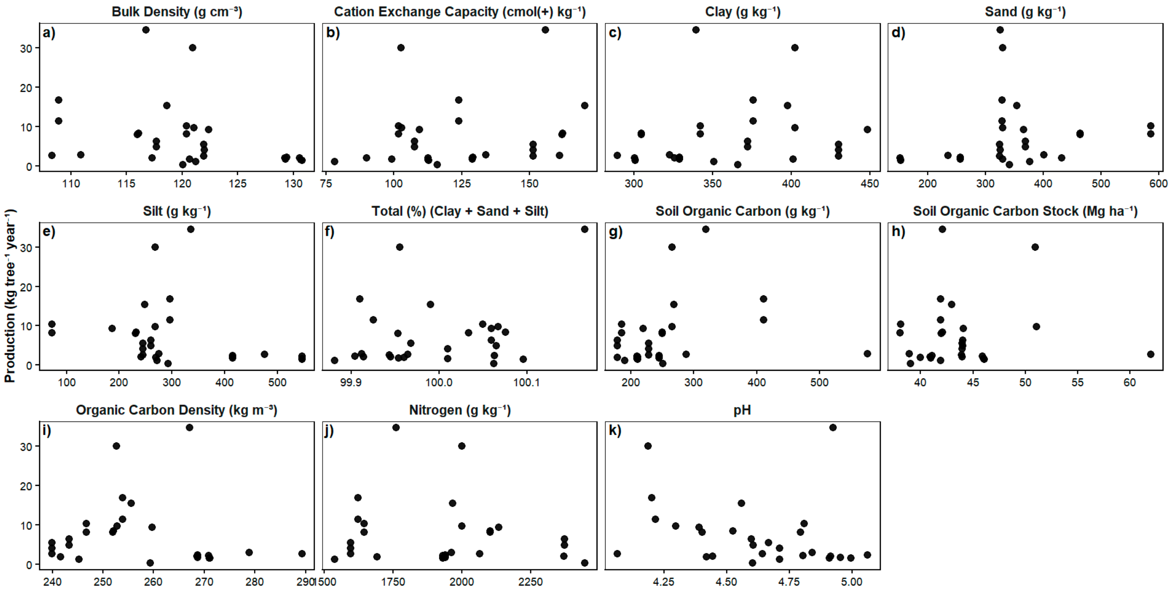

Figure 5. Relationship between fruit production of Carapa guianensis (kg tree^{-1} year^{-1}) and edaphic variables: Bulk Density (g cm^{-3}), Cation Exchange Capacity (cmol(+) kg^{-1}), Clay (g kg^{-1}), Nitrogen (g kg^{-1}), pH, Organic Carbon Density (kg m^{-3}), Sand (g kg^{-1}), Silt (g kg^{-1}), Soil Organic Carbon (g kg^{-1}), Soil Organic Carbon Stock (Mg ha^{-1}), Total (%) (Clay + Sand + Silt).

The analysis of variable importance in the Random Forest model revealed that the edaphoclimatic predictors contributing most to the variability in fruit production of *Carapa guianensis* were soil organic carbon content (%IncMSE = 5.77; IncNodePurity = 215.46) (Figure 6j), followed by mean annual temperature (%IncMSE = 5.28; IncNodePurity = 182.26) (Figure 7p), annual precipitation (%IncMSE = 2.69; IncNodePurity = 156.83) (Figure 6n), and clay content (%IncMSE = 5.52; IncNodePurity = 79.25) (Figure 6c). In addition, soil pH and silt content also showed considerable influence in the model, with IncNodePurity values of 95.67 and 94.57, respectively (Figure 6g,i). In contrast, cation exchange capacity and total nitrogen (N) exhibited relatively low influence, with %IncMSE values below 2.1 (Figure 6b,e).

The Random Forest model applied to the mean fruit production of *C. guianensis* showed satisfactory performance, explaining 42% of the observed variability in yield (RMSE = 7.79 kg·tree^{-1} and MAE = 5.25 kg·tree^{-1}) in the cross-validation analysis.

According to the relative importance of the predictors, soil organic carbon content was the most influential variable, reaching a standardized importance value of 100 in both metrics. It was followed by mean annual temperature (91.05), clay content (95.38), and annual precipitation (64.13).

Other predictors with notable contributions included soil bulk density (77.67), surface-layer organic carbon (73.99), and silt content (56.77). In contrast, variables such as cation exchange capacity and total nitrogen (N) showed very low importance, with values close to zero.

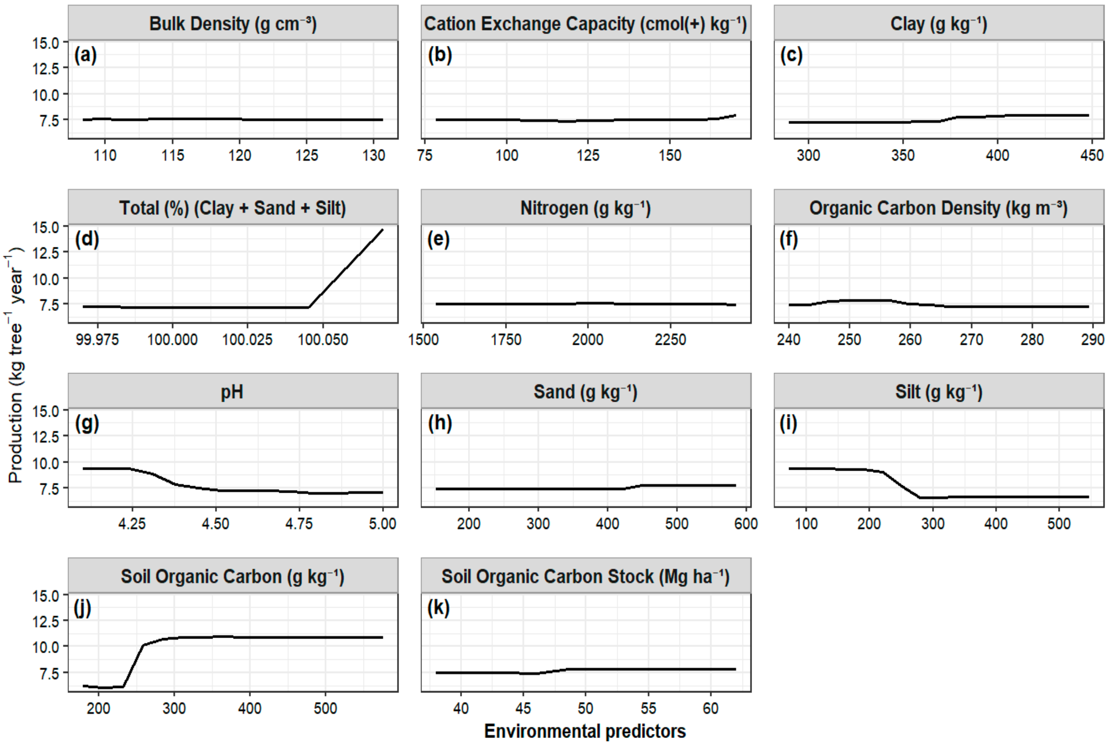

Figure 6. Partial Dependence Plots (PDP) of the environmental (edaphic) predictors on the mean fruit production of Carapa guianensis (kg tree^{-1} year^{-1}). Each panel shows the marginal effect of an individual predictor variable while the remaining variables are held constant at their average values.

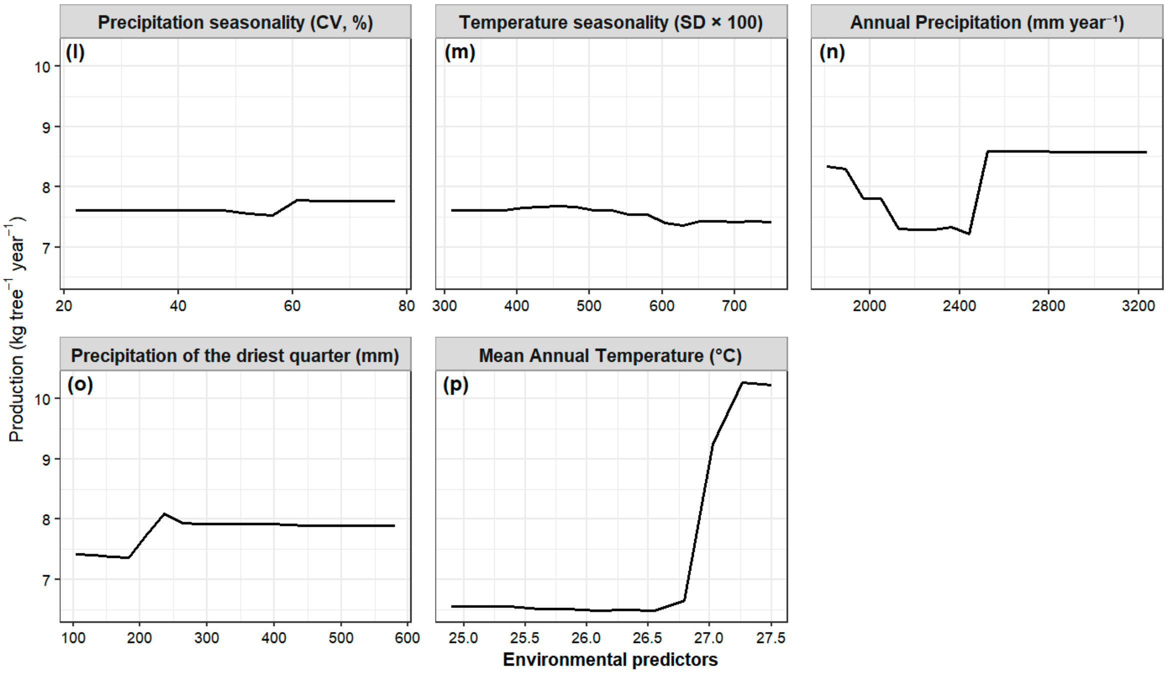

Figure 7. Partial Dependence Plots (PDP) of climatic environmental predictors on the mean fruit production of Carapa guianensis (kg tree⁻¹ yr⁻¹). Each panel shows the marginal effect of an individual predictor variable while the other variables are held constant at their mean values.

The comparison between observed and predicted values indicated a strong fit ($R^2 = 0.83$) when all data from the training set were considered (Figure 7).

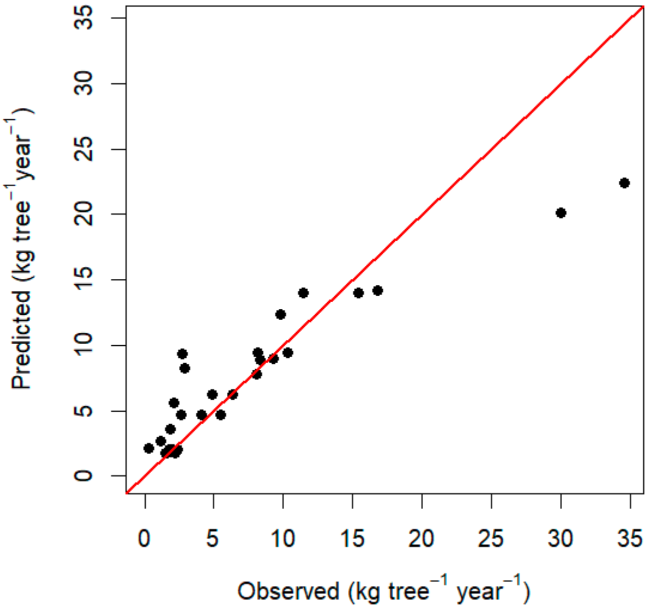

Figure 8. Observed vs. predicted values of the average fruit production of Carapa guianensis (kg tree⁻¹ year⁻¹), obtained using the Random Forest model. The red line represents the 1:1 relationship between observed and predicted values, used as a reference to assess model fit.

4. Discussion

The observed variability in fruit production of *C. guianensis* reflects the strong influence of edaphoclimatic conditions on the species' ecological and physiological processes. The observed productivity range (0.34 to 34.6 kg·tree⁻¹·year⁻¹) illustrates the spatial heterogeneity typical of Amazonian ecosystems, where soil gradients, topography, and hydrological regimes shape the productive dynamics of forest populations. Similar patterns have also been reported for other species of high ecological and economic value in the Amazon, in which phenotypic plasticity and the capacity to adapt to local conditions are key determinants [2,48]. These findings are consistent with reports by Klimas et al. [25] and Tonini et al. [53], who highlight that the phenotypic plasticity of *C. guianensis* is a critical factor underlying its broad ecological distribution.

Influence of climatic factors and forest type

The differences observed among forest types, with *várzea* forests showing the highest mean fruit production (16.55 ± 11.87 kg·tree⁻¹·year⁻¹), followed by terra firme and igapó, indicate that the hydrological and edaphic conditions characteristic of each environment exert a decisive influence on the fruiting of *C. guianensis*. Várzea environments, with more fertile soils and periodic nutrient inputs from seasonal flooding, provide particularly favorable conditions for fruit production, consistent with previous studies highlighting higher fruiting in alluvial habitats [23,36]. In contrast, igapó forests, subjected to prolonged flooding and poorer soils, exhibited the lowest fruit production. This may be attributed to physiological constraints on fruiting under more restrictive conditions, as noted by Wittmann et al. (2010).

The importance of annual precipitation and mean annual temperature in the Random Forest model supports the hypothesis that *C. guianensis* productivity is strongly influenced by water availability and thermal stability. The concentration of the highest fruit production values in regions receiving between 2,400 and 2,800 mm of annual precipitation suggests the existence of an optimal moisture range, beyond which productivity tends to decline. In this regard, studies on Amazonian tree species indicate that excessive rainfall can negatively affect production by interfering with pollination or causing drainage problems [56]. Similarly, lower thermal variability associated with higher yields suggests that *C. guianensis* may benefit from more stable temperature regimes, which would favor the synchronization of phenological events and a more efficient allocation of resources for fruit production [25,26].

Temperature also showed a non-linear relationship with fruit production, with higher yields observed in sites where the annual thermal amplitude is lower. This thermal stability may favor key physiological processes, such as the formation of reproductive buds and the accumulation of reserves in the wood, as noted by Klimas et al. [25] for tropical species with similar phenological cycles. The interaction between mean annual temperature (MAT) and annual precipitation (AP), identified by the Random Forest model, suggests that the species' productivity responds to the synergy between both climatic factors rather than to the independent effect of each one.

Importance of edaphic factors

Regarding soil properties, the prominent influence of soil organic carbon (SOC) as the main predictor (%IncMSE = 5.77; IncNodePurity = 215.46) highlights the important role of organic matter in fruit productivity. Soils with higher SOC levels typically exhibit better physical structure, greater water retention capacity, and higher nutrient availability, which promotes fruit filling and maturation [45]. This finding aligns with studies linking high organic carbon content with soil quality and productivity in Amazonian systems [6].

Soil texture, particularly the clay and silt fractions, was also identified as an important set of predictors. The values obtained for clay fraction (95.38) and silt fraction (56.77) suggest that medium-textured soils, with a balance of water retention and aeration, are more conducive to fruit production in *C. guianensis*. In contrast, sand contents above 60% were associated with lower yields, likely due to reduced moisture and nutrient retention. This relationship between texture and productivity is consistent with studies analyzing aggregate stability and organic matter dynamics in Amazonian soils [28].

Model performance and ecological implications

The Random Forest model explained 42% of the observed variability in fruit production, reflecting a moderate predictive capacity that is consistent with the complexity of Amazonian ecological systems. The high coefficient of determination obtained for the training dataset ($R^2 = 0.83$), along with the RMSE (7.79 kg·tree^{-1}) and MAE (5.25 kg·tree^{-1}) values from cross-validation, support the robustness of the model. However, these results also suggest that part of the unexplained variability could be associated with unconsidered biotic factors, such as genetic differences, pollination processes, herbivory, or intraspecific competition. Previous studies [25,56] agree that genetic variability within populations and pollinator connectivity play a key role in the productivity of *C. guianensis*.

Model performance and methodological considerations

Although the Random Forest model was able to explain 42% of the observed variability, a considerable proportion of this variability remained beyond its predictive capacity. This level of explanation is expected in tropical ecological systems, where various biotic factors, such as genetic variation among trees, pollinator efficiency, herbivory, and intra- and interspecific competition, directly influence productivity. Other elements, such as genetic variability between individuals and micro-scale edaphic or climatic gradients, may also significantly affect fruit production [1,7]. The high fit of the model on the training dataset ($R^2 = 0.83$) confirms its robustness, but it also suggests the possibility of overfitting, highlighting the importance of validating these results with new samples and in different regions.

Certain limitations of the study need to be considered, such as the use of secondary data from studies with varying methodologies and sample sizes, which may have introduced biases and increased data heterogeneity. Furthermore, the model does not directly incorporate biological or genetic variables, which could potentially explain a substantial portion of the residual variability.

Implications for management, conservation, and climate

The results obtained provide important insights for the sustainable management of *C. guianensis*, a key species with ecological and socioeconomic significance in the Amazon. The identification of soils with high organic carbon content and balanced texture as the most favorable for fruit production allows for the prioritization of areas for management and conservation. Furthermore, under a climate change scenario marked by increasing temperatures and alterations in precipitation patterns, the fruit productivity of *C. guianensis* could be compromised, affecting its availability as a natural resource and its importance for traditional communities.

Incorporating these findings into genetic conservation and forest management strategies can help maintain productive and resilient populations. The inclusion of C. guianensis in agroforestry systems or restoration programs in várzea areas can take advantage of its fruiting potential in fertile alluvial soils. In contrast, in more restrictive areas (e.g., igapó), the implementation of specific management practices could help mitigate the effects of hydrological stress and low soil fertility.

5. Conclusions

Fruit production of *C. guianensis* in the Amazon exhibits marked variation that is primarily influenced by edaphic and climatic factors, particularly soil organic carbon content, clay percentage, and mean annual temperature. Várzea environments showed the highest productivity, indicating that soils with moderate fertility and fewer hydrological constraints favor better reproductive performance of the species. These results highlight the importance of considering edaphoclimatic variables when defining potential areas for the management and conservation of *C. guianensis*, especially in the context of climate change and increasing pressures on Amazonian ecosystems. Future studies are recommended to integrate genetic and phenological aspects to better understand the interaction between environmental variability and the physiological responses of this species. This approach will help strengthen strategies for forest management and restoration in the region.

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