

EFFECTS OF THE CLIMATE GRADIENT ON THE WOOD DENSITY OF *Cedrela odorata* L. IN THE NEOTROPICAL REGION

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Resumo

Efeitos do gradiente climático na densidade da madeira de Cedrela odorata L. na região neotropical. O conhecimento das propriedades da madeira é fundamental para um melhor aproveitamento do seu potencial tecnológico, promovendo maior eficácia do uso e qualidade no produto. Entre as propriedades da madeira, a densidade é considerada como uma das mais relevantes. Vários estudos documentaram relações entre a densidade da madeira e o clima, porém, pouco se sabe sobre o papel dos fatores climáticos na variação da densidade de espécies nativas. A espécie *Cedrela odorata* L., é conhecida por possuir uma tradicional exploração madeireira no Brasil e ser amplamente distribuída na região Neotropical. Uma análise mais aprofundada dessa espécie, com foco em padrões climáticos diferentes, faz-se necessária para compreensão do potencial de resposta em diferentes regiões orientando assim seu manejo. Objetivou-se neste trabalho determinar a relação da densidade básica de *C. odorata* com as condições climáticas da região neotropical. Para isso, foi elaborado um banco de dados a partir de dados publicados em periódicos científicos. Em seguida foi realizada uma análise estatística e foram utilizados Modelos Lineares Generalizados (GLM), onde foi realizado a seleção dos melhores modelos pelo critério de informação de Akaike corrigido (AICc), para identificar possíveis padrões espaciais, foi verificado a existência de autocorrelação espacial dos dados por meio do Índice de Moran. Foram identificadas relações significativas entre a densidade do *C. odorata* e variáveis de temperatura média anual e precipitação anual. Concluiu-se que existe uma forte interação entre as variáveis climáticas analisadas e a densidade básica da madeira de *C. odorata*, sendo mais sensível a temperatura média anual.

Palavras-chave: propriedades da madeira; mudanças climáticas; temperatura média.

Abstract

Understanding wood properties is crucial for optimizing its technological potential, enhancing both the effectiveness of use and product quality. Among these properties, density is regarded as one of the most significant. Numerous studies have documented the relationship between wood density and climate. However, the influence of climatic factors on the density variation of native species remains largely unexplored. *Cedrela odorata* L., a species traditionally logged in Brazil and widely distributed across the Neotropical region, requires further analysis to understand its potential response to varying climate patterns, thereby informing its management. This study aimed to determine the relationship between the basic density of *Cedrela odorata* L. and the climatic conditions in the Neotropical region. A comprehensive database was compiled from published scientific literature. Statistical analyses were conducted using Generalized Linear Models (GLM), with the best models selected based on the corrected Akaike Information Criterion (AICc). The presence of spatial patterns was assessed using Moran's Index to verify spatial autocorrelation. The study identified significant relationships between the wood density of *C. odorata* and variables such as mean annual temperature and annual precipitation. The findings indicate a strong interaction between the climatic variables analyzed and the basic density of *Cedrela odorata* L. wood, with density being more sensitive to mean annual temperature.

Keywords: wood properties; climate change; average temperature.

INTRODUCTION

The timber industry generates \$2.6 billion annually worldwide (FAO, 2020). In Brazil alone, this value reached \$221.78 million in 2021, ranking 9th in the country's agricultural export sector, with a 9.5% growth in raw wood exports over the past ten years (MDIC, 2021). However, most of this market still focuses on non-native species. This is due to a lack of knowledge about the technological potential of native forest species, particularly in tropical regions, where forest species diversity is among the highest and least studied on the planet (SLIK *et al.*, 2015). The technological potential of a given forest species is determined by evaluating its anatomical, physical, chemical, and mechanical properties, as well as the correlations between them. Therefore, understanding wood properties is essential for the appropriate application of raw materials, enhancing usage efficiency and improving the final product's quality.

The basic wood density (specific mass) results from the combination of the anatomical, physical, and chemical properties of the wood and is frequently considered a key characteristic (BURGUER; RICHTER, 1991) and one of the most significant. The basic wood density is calculated by the ratio of the oven-dry mass to the volume of wood above the fiber saturation point. It is used in various segments of the forestry sector due to its influence on characteristics such as mechanical strength, degree of instability, combustibility, and the wood's behavior in applications involving adhesives and pulping (BURGUER; RICHTER, 1991). Beyond these industrial and ecological implications, wood density is a critical component in biomass estimation procedures and forest carbon stock assessments (CLOUGH *et al.*, 2017).

From an ecophysiological perspective, trees respond physiologically to climatic conditions, leading to changes in their wood, which affect the quantity and characteristics of xylem cells, as well as the properties of growth rings and, consequently, their basic density. There is significant evidence of the relationship between wood density and geographical and climatic factors (NABAIS *et al.*, 2018; KURZ-BESSON *et al.*, 2016). Thus, higher wood density is associated with slow growth rates and low mortality due to its competitive potential (KUNSTLER *et al.*, 2015).

In this study, we used *Cedrela odorata* L. (cedarwood), a species from the genus *Cedrela* and the family Meliaceae, chosen for its native status in the neotropical region, wide distribution, and traditional timber use in Brazil. In Brazil, it is found in the Cerrado, Atlantic Forest, Caatinga, and Amazon Rainforest (FLORES, 2020). The wood exhibits dimensional stability, as evidenced by its anisotropy coefficient of 1.2, and it has little tendency to develop defects during the drying process, making it suitable for high-end uses in furniture, boats, musical instruments, and bathtubs (FERNANDES *et al.*, 2018). However, due to its high commercial value, *Cedrela odorata* L. wood faces significant pressure from the timber industry, necessitating proper management for species preservation (BRANDES *et al.*, 2020).

Dendrochronological studies on *Cedrela odorata* L. wood have shown that seasonal growth rhythms are particularly influenced by intra-annual climatic variations, especially in relation to the rainy season (MENEZES *et al.*, 2022; DA COSTA *et al.*, 2023). Studies have documented relationships between wood density and climate, as well as other resource gradients such as soil fertility, silvicultural practices, competition, and age (CASTRO *et al.*, 2020; KUNSTLER *et al.*, 2015). However, little is known about the role of climatic factors in the variation of cedarwood density. Therefore, this study aimed to determine the relationship between the basic density of *C. odorata* and climatic conditions in the neotropical region.

MATERIAL AND METHODS

Density data

The wood density database for *Cedrela odorata* L. was compiled through searches on Google Scholar, ResearchGate, Web of Science, Scielo, and available databases such as DRYAD and the ICRAF DATABASE. No geographical limits were set for the compilation of the database.

The selection of publications was based on the following criteria:

- Publications with basic wood density data derived from tests;
- Geographic coordinates indicated;
- If geographic coordinates were not mentioned, the location (city) where the wood was collected had to be specified;
- In assays involving trees of different ages or density data obtained from different segments (e.g., heartwood and sapwood), the average value was used.

Climatic data

Climatic data were obtained from WorldClim (FICK; HIJMANS, 2017) for the geographic coordinates of the selected publications. Annual mean temperature (°C) and annual precipitation (mm) data were extracted with a spatial resolution of 30 arc-seconds.

Statistical analysis

The analysis began by assessing the assumptions for using multiple linear regression analysis, which included: (i) normality of the response variable data; (ii) absence of autocorrelation among independent variables; and (iii) normality in the distribution of regression residuals. Normality was tested using the Shapiro-Wilk test. Autocorrelation was tested with Pearson's linear correlation test. Once these assumptions were met, Generalized Linear Models (GLM) were applied, considering wood density as the dependent variable and annual mean temperature (°C) and annual precipitation (mm) as predictor variables. Interaction between the independent variables was also considered in these models. Thus, the global model was formulated as:

Wood Density ~ Annual Mean Temperature * Annual Precipitation

Where “*” represents the interaction between the independent variables.

To select the best models from the global model, we used the corrected Akaike Information Criterion (AICc), comparing all combinations of variables, along with the null model. The best models were those with AIC values ≤ 2 (BURNHAM; ANDERSON, 2002). The MuMIn package was used for model selection. The dredge function generated all variable combinations from the global model and ranked them according to the established AICc. The significance values of the predictor variables were obtained for the best models.

To identify possible spatial patterns, we checked for spatial autocorrelation in the data using Moran's Index with the testSpatialAutocorrelation function from the DHARMA package and the moran.test function from the spdep package.

All analyses and graphics were performed using R software (R core team, 2020).

RESULTS

Twenty-four density data points for *Cedrela odorata* L. were collected from experimental trials. All data meeting the prerequisites are located in the Neotropical region. The geographic distribution of the density data for *Cedrela* is presented in Figure 1 and Table 1.

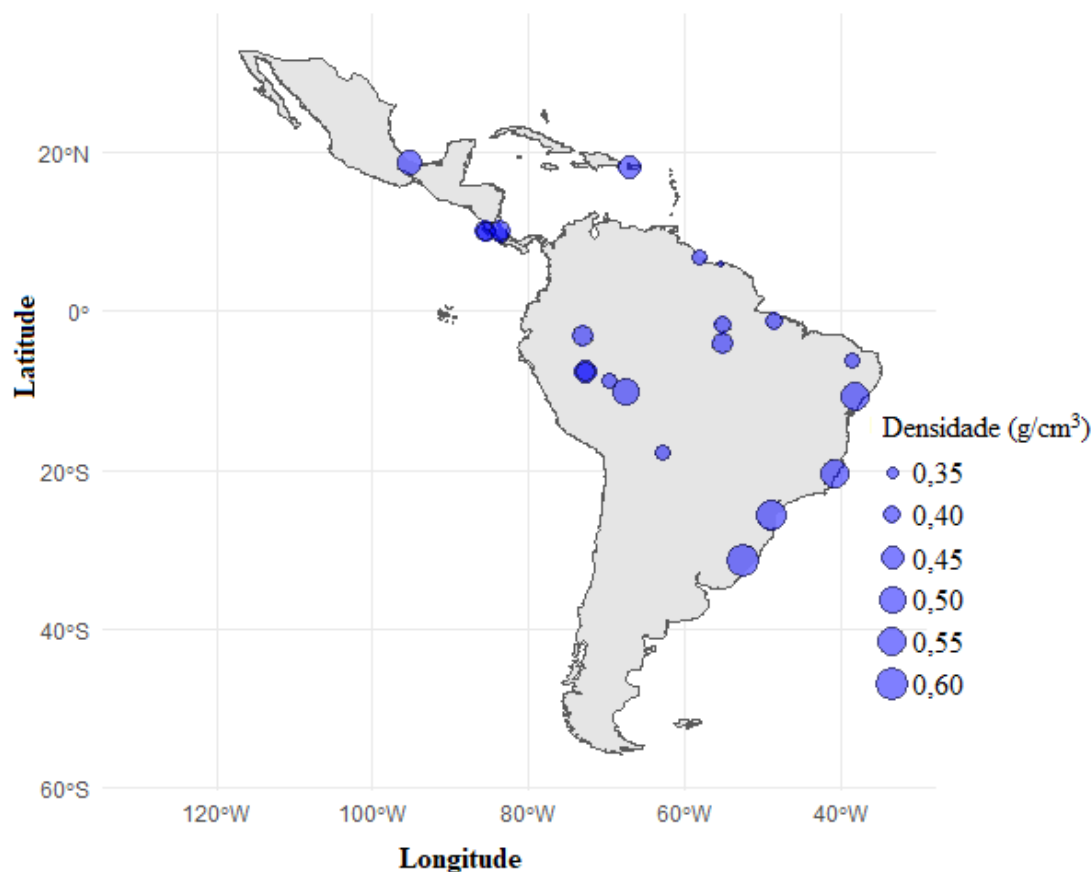


Figure 1 - Distribution map of density data ($\text{g} \cdot \text{cm}^{-3}$) of *Cedrela odorata* L.

Figura 1 - Mapa de distribuição dos dados de densidade ($\text{g} \cdot \text{cm}^{-3}$) de *Cedrela odorata* L.

Table 1 – Relationship between the density of *Cedrela odorata* L. and locations.

Tabela 1 – Relação entre densidade de *Cedrela odorata* L. e locais.

Density (g/cm ³)	Latitude	Longitude	Title of the study
0.44	4°04'46.4"S	54°54'22.9"W	doi: https://doi.org/10.2737/SO-GTR-88
0.43	10°03'28.7"N	85°25'15.8"W	Malavassi IMC. Maderas de Costa Rica: 150 Especies forestales. Costa Rica: Editorial de la Universidad de Costa Rica; 2003. 340p. ISBN 9977-67-725-8
0.34	10°23'00.6"N	85°20'03.8"W	doi: https://doi.org/10.2307/244454
0.45	18°09'01.6"N	66°59'12.6"W	Little EL, Wadesworth FH. Common trees of Puerto Rico and the Virgin Islands. US Department of Agriculture, Washington: US Government Printing Office; 1964. Agricultural Handbook 249. ASIN : B001S5SDBO
0.42	3°15'26.2"S	72°55'03.3"W	Arostegui A. Estudio tecnológico de maderas de Perú (zona Pucallpa). Características y usos de la madera de 145 especies del país.. Lima: Universidad Nacional Agraria La Molina; 1974. v. 1.
0.379	6°48'05.7"N	58°09'10.3"W	Fanshawe, DB. Forest products of British Guiana I: principal timbers. Forestry Bulletin (New Series). Forest Department, Georgetown, British Guiana By H ter Steege. 1961.
0.39	1°26'09.6"S	48°26'57.1"W	doi: http://www.ibama.gov.br/lpf/madeira/default.htm
0.38	17°51'49.7"S	62°49'33.3"W	Gutierrez Rojas VH, Sandoval IJS. Informacion Technica para el Procesamiento Industrial de 134 Especies Maderables de Bolivia. Serie Tecnica XII. Ministerio de Desarrollo Sostenible y Planificacion. Santa Cruz, La Paz, Bolivia, 2004
0.568	25°43'01.3"S	48°51'30.0"W	doi: http://comexstat.mdic.gov.br/pt/home
0.34	5°53'03.0"N	55°09'29.6"W	Vink AT. Surinam Timbers. State Forest Industries, Paramaribo, Suriname :H Muller-Landau. 1983.
0.39	1°53'17.1"S	55°07'03.7"W	doi: https://doi.org/10.1016/S0378-1127(96)03840-6
0.4675	13°39'56.9"S	172°32'00.3"W	Lemmens RHMJ, Soerjanegara I, Wong WC. Plant Resources of South-East Asia Timber trees: Minor commercial timbers. Leiden: Backhuys Publishers. 1995. v 5. ISBN 90-5782-042-0
0.48	18°33'45.7"N	95°11'58.8"W	doi: https://doi.org/10.1163/22941932-90001041
0.38	9°24'57.6"N	83°41'34.5"W	doi: https://doi.org/10.2737/SO-GTR-88
0.46	7°37'24.6"S	72°42'14.6"W	Calderon CM, Lopes E, Fernandes NCL, Amorim P, Calderon RA. Avaliação das propriedades físicas da madeira de Cedrela Odorata L. no município de Cruzeiro do Sul-AC. In: Congresso Brasileiro de Ciência e Tecnologia da Madeira 2013, Campinas: 2013, São Paulo. Anais [...].
0.41	7°37'24.6"S	72°42'14.6"W	doi: https://doi.org/10.1590/2179-8087.100814
0.51	10°04'21.8"S	67°37'39.7"W	Dias FM, Lahr FAR. Estimativa de propriedades de resistência e rigidez da madeira através da densidade aparente. Scientia Forestalis, 2004;65:102-113
0.383	8°51'55.5"S	69°40'01.3"W	doi: https://doi.org/10.21577/0100-4042.20170014
0.54	10°47'04.2"S	38°00'45.5"W	Anholetto-Jr C.R. 2013. Dendroecologia e composição isotópica (δ13C) dos anéis de crescimento de árvores de Cedrela odorata, Meliaceae, na Caatinga e Mata Atlântica do estado de Sergipe, Brasil. Dissertação de Mestrado, Universidade de São Paulo, Piracicaba.
0.539	20°35'21.3"S	40°30'45.4"W	Catein FA. Caracterização da madeira de <i>Cedrela odorata</i> destinada a fabricação de ofurô. 2019. 65 f. Trabalho de Conclusão de Curso (Graduação em Engenharia Industrial Madeireira) – Departamento de Ciências Florestais e da Madeira, Universidade Federal do Espírito Santo, Jerônimo Monteiro.

0.41	9°56'58.5"N	85°21'58.9"W	doi: https://doi.org/10.29298/rmcf.v11i57.556
0.37	6°06'15.8"S	38°24'39.1"W	doi: https://doi.org/10.33448/rsd-v9i8.5614
0.61	31°32'13.5"S	52°30'15.8"W	Cademartori PH, Gatto DA, Stangerlin D, Calegari L. DESCRIÇÃO MACROSCÓPICA DAS MADEIRAS DE <i>Cedrela fissilis</i> Vell., <i>Cedrela odorata</i> L. E <i>Cedrelinga catenaeformis</i> Ducke. XII Encontro Brasileiro em Madeiras e em Estruturas de Madeiras, 2010
0.44	9°58'06.9"N	83°37'15.2"W	doi: https://doi.org/10.21829/myb.2018.2411485

The analysis of density data for the normality test, according to the Shapiro-Wilk test, showed a W statistic of 0.93168, with a p-value of 0.1063, accepting the hypothesis of data normality at a significance level of $\alpha=0.05$. The density had a mean of approximately $\cong 0,439 \pm 0,072 \text{ g} \cdot \text{cm}^{-3}$. The highest density was $0.61 \text{ g} \cdot \text{cm}^{-3}$ and the lowest was $0.34 \text{ g} \cdot \text{cm}^{-3}$.

Pearson's correlation coefficient indicated no association between temperature and precipitation, with a correlation coefficient of -0.05016666 and a p-value of 0.8159. Therefore, both climatic variables and their interaction were used in the statistical model.

The application of Generalized Linear Models (GLM) to predict the density of *Cedrela odorata* L. (D) as a function of annual precipitation (P), annual mean temperature (T), and error (ε) yielded the best fit in Equation 1, with an AICc of -73.3 and a log-likelihood function (logLik) of 43.293, representing 88.7% of the data:

$$\text{Eq. 1- } D = 1.8170 - 4.581e^{-0.4} \cdot P - 5.722e^{-0.2} \cdot T + 1.912e^{-0.5} \cdot P \cdot T + \varepsilon$$

All variables were significant (Table 2), allowing the model to accurately estimate the response variable, density, for *C. odorata* wood. The wood density of *Cedrela odorata* L. showed an inverse relationship with temperature and precipitation (Figure 2). The absence of spatial autocorrelation in the dataset, as indicated by Moran's Index, confirmed the spatial independence of the model.

Table 2 - Model estimates, standard error, and significance associated with each estimate

Tabela 2 - Estimativas do modelo, erro-padrão e significância associado a cada estimativa

	Estimates	Standard error	T-value	Pr > t	
Intercept	1.817	$2.981 \text{ e}^{-0.1}$	6.095	$5.89 \text{ e}^{-0.6}$	***
Rainfall	$-4.581 \text{ e}^{-0.4}$	$1.457 \text{ e}^{-0.4}$	-3.144	0.005110	**
Temperature	-0.05722	$1.291 \text{ e}^{-0.2}$	-4.433	0.000256	***
Rainfall*temperature	$1.912 \text{ e}^{-0.5}$	$6.344 \text{ e}^{-0.6}$	3.013	0.006872	**
Signif. Codes:	0 '***' 0.001 '**' 0.01 '*' 0.5 '.' 0.1 ' ' 1				

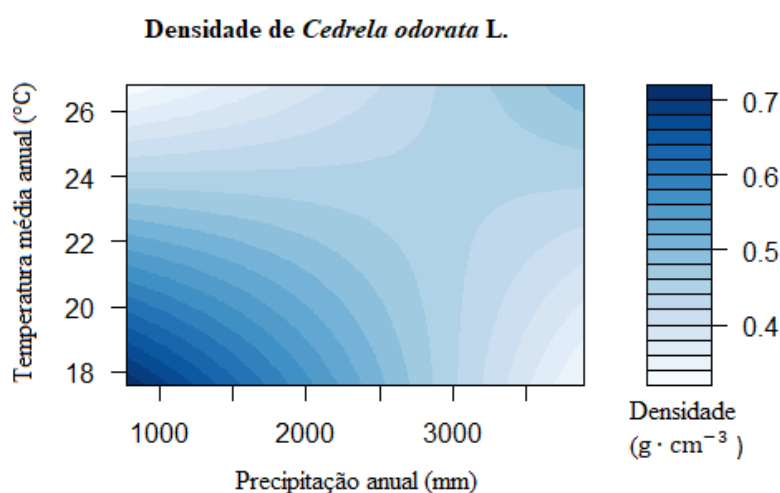


Figure 2 – Relationship between the density of *Cedrela odorata* L. wood and climatic variables. Darker tones represent a higher density value.

Figura 2 – Relação entre a densidade da madeira de *Cedrela odorata* L. e variáveis climáticas. Tons mais escuros representam um valor maior de densidade.

DISCUSSION

The results corroborated the expected hypotheses, showing that the basic wood density of *Cedrela odorata* L. has a strong relationship with climatic characteristics within its Neotropical occurrence gradient. Thus, the highest wood densities of the studied species are found under conditions of lower average temperatures and lower annual precipitation, while moderate densities are found in mild temperatures and higher annual precipitation. Therefore, these results can assist in decision-making regarding planting locations, depending on the intended use of the wood, as the location and environment of a forest influence its production and development (SANTOS *et al.*, 2012).

The low variance of $0.072 \text{ g}\cdot\text{cm}^{-3}$ confirms that, although wood density varies significantly across different sites, the range is limited, suggesting that the average wood density of *Cedrela* is highly conserved phylogenetically (CHAVE *et al.*, 2006). As mentioned, different density classes are desired depending on the intended use. The Brazilian Forest Service classifies commercially used woods in Brazil as low-density if the specific gravity is up to $0.50 \text{ g}\cdot\text{cm}^{-3}$, medium-density between $0.5 \text{ g}\cdot\text{cm}^{-3}$ and $0.72 \text{ g}\cdot\text{cm}^{-3}$, and high-density above $0.72 \text{ g}\cdot\text{cm}^{-3}$ (RUFFINATTO *et al.*, 2015). For example, for pulp production, lower-density wood is preferred as it results in better pulp yield and pulping process efficiency (QUEIROZ *et al.*, 2004). In the case of charcoal production, higher wood densities are desired since denser charcoal has more energy per unit volume and greater mechanical strength in blast furnaces (COSTA *et al.*, 2014). The same applies to civil construction, where density directly influences the mechanical strength of the wood; the higher the basic density, the greater the strength (LOBÃO *et al.*, 2004). For furniture making, the desired density may vary depending on the type of furniture being manufactured.

A significant relationship was found between wood density and the interaction between precipitation and temperature. Locations with lower temperatures and lower precipitation exhibited higher densities. These factors impact the quantity and characteristics of xylem cells, as well as the properties of growth rings and their density in *Cedrela odorata* (KURZ-BESSON *et al.*, 2016). Dendrochronological studies indicate a strong relationship between cedar cambial activity and precipitation. The onset of wood growth in this species is positively related to the rains of the previous season, indicating a water reserve mobilized in the next growth season (LISI *et al.*, 2020). Thus, with high precipitation, there is a greater proportion of earlywood, formed at the beginning of the growth season, compared to latewood. The cambial activity of *C. odorata* is also strongly influenced by temperature; studies indicate that an increase in temperature induces vascular cambium activity. In contrast, a decrease in temperature is associated with reduced cell diameter, thickening of the cell wall, reduced cambial activity, and consequently, increased wood density (BEGUN *et al.*, 2017).

C. odorata is well-known for its growth dynamics and ring formation during its well-defined cambial activity. Its wood exhibits a higher concentration of larger diameter vessels at the beginning of the growth period and a lower concentration of smaller diameter vessels at the end, resulting in lower density in earlywood (ESPINOZA *et al.*, 2014). Albuquerque *et al.* (2016) found density values of $0.2 \text{ g}\cdot\text{cm}^{-3}$ in earlywood and $0.5 \text{ g}\cdot\text{cm}^{-3}$ in latewood. As a result of the higher proportion of earlywood in areas with high precipitation, cedar has lower wood densities. Generally, growth-favorable environments, which result in a higher rate of cell division, are not usually accompanied by cell wall thickening, leading to lower wood density due to a lower proportion of latewood relative to earlywood (BERGÈS *et al.*, 2008).

In most cases, wood density was positively correlated with drier climates, indicating that, at least for *Cedrela odorata*, higher density is an adaptive trait associated with drought tolerance (CLOUGH *et al.*, 2017). However, higher average density in some humid areas with higher temperatures was also observed, which may suggest an evolutionary characteristic due to other stimuli present in the location (Sette Jr *et al.*, 2016). THOMAS *et al.* (2007) observed that an increase in temperature marginally reduced the diameter of wood fiber cells, and this, combined with changes in cell wall thickness, reduced the lumen diameter of the fiber. However, at supra-optimal temperatures, a reduction in density was observed. In their model, higher temperatures resulted in increased cell production, but at supra-optimal temperatures, the cell production rate decreased. This suggests that other unaccounted factors, besides climate (e.g., age, competition, soil fertility, pathogen resistance), may also be strong drivers of wood density variation (NABAIS *et al.*, 2018).

Understanding the intraspecific variation in wood density in relation to climatic conditions can guide wood utilization, assist in proper management for species conservation, and elucidate ecological processes in forests over large spatial extents. A more in-depth analysis of the species is needed, focusing on wood anatomy (fiber characteristics, parenchyma tissue, pores, and rays), along with local climate data and other factors influencing wood density that may further explain the variability in cedar wood density in the Neotropical region (such as competition, soil fertility, pathogen resistance).

CONCLUSION

Based on the data evaluated in this study for *Cedrela odorata* L., it can be concluded that:

- There is a strong interaction between climatic variations and the basic wood density, despite the low variance in density values, confirming a high level of phylogenetic control in the species.
- Significant relationships were identified between the density of *Cedrela odorata* and variables such as average annual temperature and annual precipitation. For *C. odorata*, density showed greater sensitivity to temperature.

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