Journal of Forestry Research (2026) 37:73
https://doi.org/10.1007/s11676-026-02012-3

ORIGINAL PAPER

Radial growth of *Cedrela odorata* L. in two areas with over 160 years of distinct forest recuperation pathways: active reforestation vs. natural regeneration

Raphaella Moreira Pierre[1] · Warlen Silva da Costa[1] · Daniela Granato[2] · Gabriel Paes da Silva Sales[3] · Rejan Rodrigues Guedes-Bruni[3] · Cátia Henriques Callado[1]

Received: 25 June 2025 / Accepted: 26 October 2025
© The Author(s) 2026

Abstract Forest restoration plays an essential role in mitigating climate change, conserving biodiversity, and maintaining ecosystem services. Altough global initiatives emphasize the urgency of developing effective strategies for ecosystem recovery, assessing the success of these strategies remains a considerable challenge. In this context, we investigated the growth dynamics of *Cedrela odorata* L. (Meliaceae) over more than 160 years in two Atlantic Forest areas in Rio de Janeiro, Brazil, characterized by distinct historical recuperation pathways: active reforestation in Parque Nacional da Tijuca (PNT) and natural regeneration following land protection in Reserva Biológica do Tinguá (RBT). Dendrochronological analyses revealed significant differences in age structure and tree size between areas. Trees in PNT were older and larger (169 years, DBH 78 cm) than those in RBT (132 years, DBH 56 cm), reflecting differences in management intensity. Higher growth rates during early development of trees in PNT are likely associated with silvicultural practices implemented during reforestation. However, from the 1940s onwards, a convergence in growth rates indicates structural recovery in both areas. This pattern reflects increased competition among trees, characteristic of more advanced stages of forest dynamics. After 1990, both areas experienced a decline in growth, potentially linked to increasing urban-related environmental stressors. Overall, our results highlight the resilience of *C. odorata* and emphasize the importance of forest recuperation efforts in both areas, demonstrating their long-term success. Additionally, they underscore the effectiveness of restoration practices in PNT, as demonstrated by the acceleration of structural recovery in the forest, with older trees, increased aboveground biomass, and radial increment rates comparable to those of mature forests. This success also implies the restoration of ecosystem services, as sought in the historical recovery proposals for these two tropical forest areas.

Keywords Radial growth comparative analysis · Dendroecology · Historical wood anatomy · Dense ombrophilous rainforest · Forest restoration indicators

Introduction

The occupation of the Brazilian coast has undergone disorganized cycles of natural resource exploitation and urbanization, threatening the Atlantic Forest since the sixteenth century (Dean 1996; Marques and Grelle 2021). Intense deforestation throughout the nineteenth century, primarily driven by coffee monoculture, played a significant role in the severe droughts that affected the city of Rio de Janeiro during that period (Drummond 1988; Dean 1996; da Silva Sales and Guedes-Bruni 2018, 2023).

In 1833, Emperor Dom Pedro II decreed the expropriation of cultivated lands, which now forms part of the Reserva

The online version is available at https://link.springer.com/.

Corresponding editor: Tao Xu.

✉ Cátia Henriques Callado
catia.callado@gmail.com; ccallado@uerj.br

[1] Laboratório de Anatomia Vegetal, Programa de Pós-Graduação Em Biologia Vegetal, Instituto de Biologia Roberto Alcantara Gomes, Universidade Do Estado Do Rio de Janeiro, Rua São Francisco Xavier, 524-PHLC, sala 224, Rio de Janeiro, RJ 20550-013, Brazil

[2] Department of Geosciences, University of Arkansas, Fayetteville, AR 72701, USA

[3] Departamento de Biologia, Pontifícia Universidade Católica do Rio de Janeiro, Gávea, Rio de Janeiro, RJ 22451-000, Brazil

Biológica do Tinguá (RBT) (IBAMA 2006; Leitão et al. 2023). This initiative aimed to restore forest areas to increase the water supply for the city of Rio de Janeiro. In 1861, Dom Pedro II issued another decree to secure the water supply for the city, outlining provisional guidelines for the planting and recovery of the forests of Tijuca and Paineiras. This decree initiated the reforestation of the Maciço da Tijuca, now part of the Parque Nacional da Tijuca (PNT) (Brasil 1967). Together, these efforts—focused on protecting lands for natural succession and active forest restoration—were among the first steps in Brazil to safeguard water sources and mitigate the problems of severe droughts and floods that were experienced in the mid-nineteenth century, through the creation of "Protective Forests" in Rio de Janeiro State (da Silva Sales and Guedes-Bruni 2024).

In the current context of the climate emergency, the droughts and floods experienced in Atlantic Forest regions in Brazil are critically relevant (da Silva Sales and Guedes-Bruni 2018, 2023). The Atlantic Forest is projected to be among the Brazilian biomes most affected by climate change (Scarano and Ceotto 2015). Its original distribution covered over 1.6 million km^2, primarily along Brazil's coastline (Ribeiro et al. 2009, 2011). Today, only 12.4% of its original area remains (Ribeiro et al. 2009), with an estimated loss of 3.4 hectares per hour (INPE 2022). Even more than in the past, restoring and maintaining forests remains fundamental for improving food and water security, reducing the risk of diseases and pests, preventing biodiversity loss, and mitigating climate change (Netherlands Environmental Assessment Agency 2020). Numerous global initiatives aim to enhance commitments and actions to prevent and reverse ecosystem degradation, such as the UN Decade on Ecosystem Restoration and the Kunming-Montreal Global Biodiversity Framework (United Nations 2020; Conference of the Parties to the Convention on Biological Diversity 2022).

Although the concept of ecological restoration was established early in the twentieth century (Higgs 2003), there remains no consensus regarding the relative importance of each attribute used to assess the effectiveness of restoration projects (Brancalion et al. 2015). Most assessments of forest restoration rely on compositional metrics, such as plant species richness and abundance, as well as structural metrics, including plant height and stem diameter (Gatica-Saavedra et al. 2017). Indicators based on functional traits have only recently begun to be adopted. These indicators may include nutrient acquisition strategies (*e.g.*, P and N), pollination syndromes, dispersal syndromes, life forms and life spans, survival rates, growth and reproduction, competitive capacity, stress tolerance, resistance and resilience to disturbances, as well as above and below-ground biomass, among others (Brancalion and Holl 2016; Derhé et al. 2016; Carlucci et al. 2020; Loureiro et al. 2023; dos Reis and Nascimento 2024). Indeed, analysing multiple variables can enhance the ability to assess restoration efforts (Gatica-Saavedra et al. 2017).

This study hypothesizes that functional traits of long-lived plants can provide insights into the effectiveness of forest restoration. Specifically, it aims to compare life expectancy, radial growth rates (a proxy for above-ground biomass accumulation), and resistance/resilience to the urban evolution of Rio de Janeiro, the fourth-largest city in Latin America. To do so, we analysed the growth rings of *Cedrela odorata* L. trees in two Atlantic Forest areas that were restored nearly two centuries ago through different initiatives: active reforestation with timber species in the Parque Nacional da Tijuca (PNT) and natural regeneration resulting from the prohibition of tree cutting in Reserva Biológica do Tinguá (RBT).

Materials and methods

The botanical family Meliaceae, comprising large trees inhabiting tropical and subtropical regions, has its centre of diversity in the Neotropics, with over 800 species distributed from lowland rainforests to high Andean altitudes (Gentry 1988). In Brazil, this family is among the richest in tree and shrub species (Forman et al. 1975; Zappi et al. 2015), including *Cedrela fissilis* Vell. and *C. odorata* L. (Stefano et al. 2015).

Cedrela odorata L., commonly known as Spanish cedar, is a globally valued timber species with uses in furniture, handicrafts, and traditional medicine (IUCN 2017). Despite its economic and ecological importance, it is threatened by unsustainable harvesting practices and habitat destruction, resulting in its classification as "Vulnerable" on the IUCN Red List (IUCN 2017; Costa et al. 2024).

The species is recommended for reforestation of degraded areas due its role as a shade tree (IUCN 2017) and it is typically associated with secondary stages of natural succession (Blagitz et al. 2019). Its growth exhibits seasonal rhythms (Worbes 1999; Tomazello Filho et al. 2000; Brienen and Zuidema 2005, 2006; Costa et al. 2013, 2024; Baker et al. 2016) characterized in Rio de Janeiro State by leaf shedding and cambial dormancy during the dry season, typically from May to August (Costa et al. 2013).

This study was conducted in two Atlantic Forest areas in Rio de Janeiro State, Brazil, approximately 50 km apart: Parque Nacional da Tijuca (PNT) and Reserva Biológica do Tinguá (RBT). Located in the municipality of Rio de Janeiro (22°55' S–23°00' S, 43°11' W– 43°19' W), PNT encompasses four sectors (Floresta da Tijuca, Serra da Carioca, Pedra Bonita/Pedra da Gávea and Pretos Forros/Covanca) and covers ~ 4,000 ha (ICMBio 2008; da Silva Sales and Guedes-Bruni 2023). RBT extends across six municipalities (22°22' S–22°45' S, 43°40' W– 43°05' W),

covering ~ 25,000 ha (IBAMA 2006). Both areas are characterized by having a tropical rainy climate (Aw) (IBAMA 2006; ICMBio 2008; Alvares et al. 2014) and predominantly Dense Ombrophilous Forests in advanced stages of regeneration (Abreu 1992; IBAMA 2006; ICMBio 2008).

Monthly temperature and precipitation data were obtained from the meteorological database of the National Oceanic and Atmospheric Administration (NOAA), with interpolated averages from the nearest weather stations to the study areas (Fig. 1).

Samples of *C. odorata* were collected in two different periods. In PNT, 20 individuals were sampled by the authors between 2019 and 2023. In RBT, 30 individuals were sampled between 2010 and 2012, during previous research projects carried out in the area (Costa et al. 2013, 2024; Arêdes-dos-Reis et al. 2016, 2019). Thus, a total of 50 trees with a minimum diameter at breast height (DBH, measured at 1.30 m above the ground) of 16 cm were sampled (20 from PNT and 30 from RBT) (Appendix Table S1). PNT sampling locations were selected based on historical, geographical, and floristic evidence of reforestation sites (da Silva Sales and Guedes-Bruni 2023).

Two to four increment cores were extracted from each tree using a non-destructive method with a Pressler increment borer at 1.30 m above ground level. Cores were air-dried at room temperature and then polished on the transverse face with progressively finer sandpaper. Growth rings were identified and marked under a stereomicroscope, based on species-specific anatomical descriptions (Tomazello Filho et al. 2000; Dünisch et al. 2002; Costa et al. 2013; Lisi et al. 2020).

Growth rates were calculated following the methodology described by Costa et al. (2015). Cumulative Radial Increment (CRI) was calculated by summing the width of each growth ring with that of the preceding ring. CRI values were plotted by study area, regardless of tree age, to evaluate trends in radial growth stabilization. Diametric Annual Increment (DAI) was calculated by dividing CRI by the number of rings per tree and multiplying the results by two. The relationship between tree diameter and age was assessed

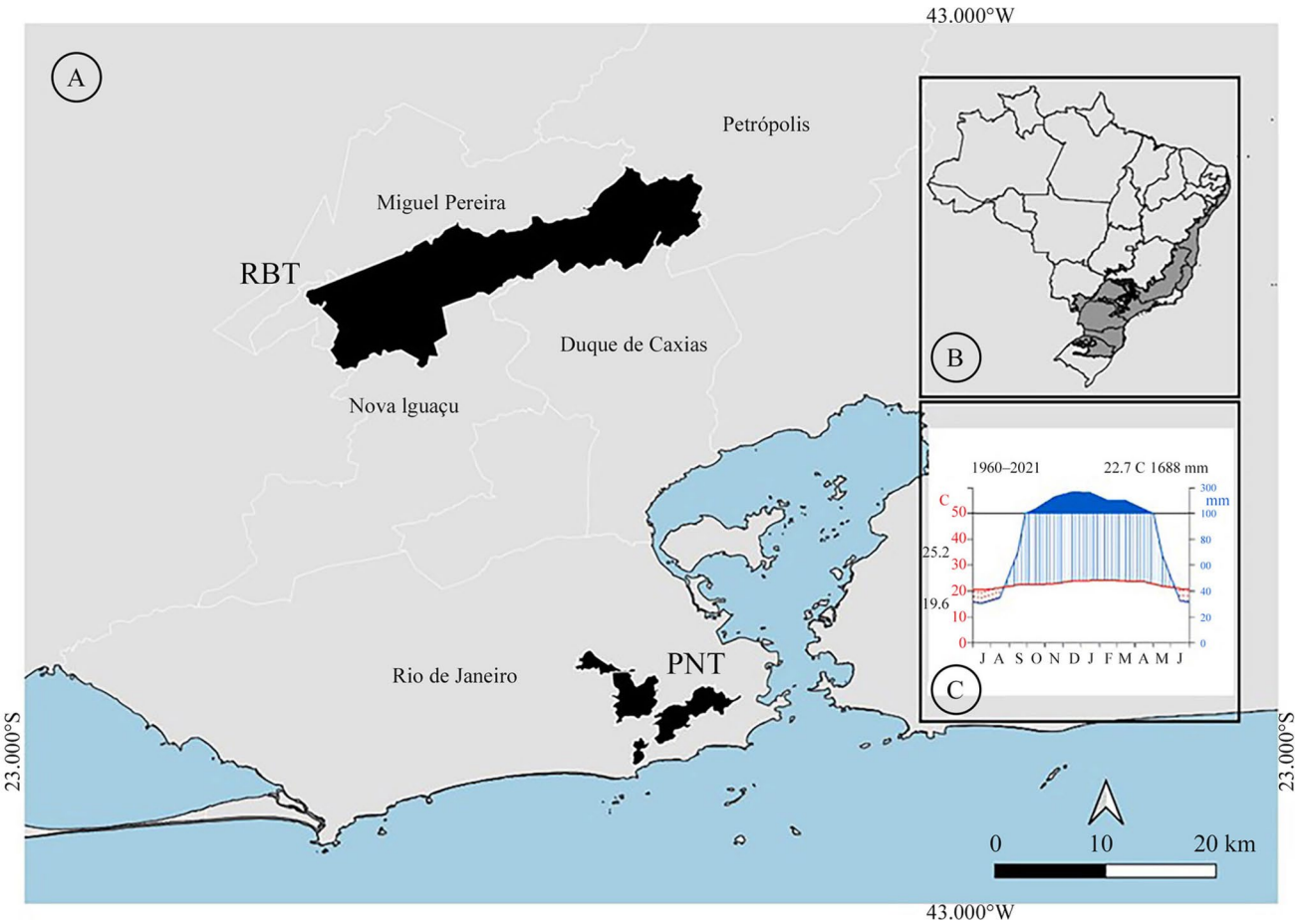


Fig. 1 **A** Location of the two study areas in Rio de Janeiro State; **B** Map of Brazil. Light gray = extent of the Atlantic Forest; **C** Climatic diagram showing the average temperature and precipitation for the study areas. PNT = Parque Nacional da Tijuca; RBT = Reserva Biológica do Tinguá

using Pearson correlation analysis, with results presented as box plots. Additionally, scatter plots were used to illustrate the relationship between age and diameter at breast height (DBH) across both study areas.

Mean growth ring widths were compared across years for trees sampled in each study area. To ensure reliable comparisons, all comparative analyses of mean ring width were restricted to the overlapping interval of 1901–2010. This temporal alignment was adopted to minimize potential bias from non-synchronous sampling. Moreover, only years with data from at least two individuals per area were included, further enhancing comparability. This interval was further subdivided into three time periods: 1901–1940, 1941–1989, and 1990–2010, based on observed shifts in growth ring width trajectories. Kolmogorov–Smirnov and Levene's tests were applied to assess normality and homogeneity of variances, respectively. Due to the non-parametric nature of the data, the Mann–Whitney test was employed to detect statistically significant differences in growth ring widths between the two areas within each time interval. All statistical analyses were performed using Statistica 7 software.

Results

The growth rings of *C. odorata* were identified based on the presence of marginal parenchyma and the semi-porous distribution of vessel elements. Statistically significant differences were observed between the study areas for both tree age and diameter at breast height (DBH) (Fig. 2). In the reforested area (PNT–Parque Nacional da Tijuca), the sampled trees had a mean age of 93 years, a mean DBH of 78 cm, and a mean DAI of 5.74 mm. In the naturally regenerated area (RBT–Reserva Biológica do Tinguá), the mean age was 73 years, the mean DBH was 56 cm, and the mean DAI was 5.69 mm (Appendix Table S1, Fig. 2).

Tree age in PNT ranged from 31 to 169 years, DBH from 16 to 150 cm, and DAI from 2.7 to 11.36 mm (Appendix Table S1). In RBT, tree age ranged from 20 to 132 years, DBH from 16.40 to 115.61 cm, and DAI from 2.43 to 12.08 mm (Appendix Table S1). In PNT, three individuals over 100 years old (100, 102, and 125 years) exhibited DAIs equal to or above the area average. This trend was not observed in RBT, where individuals with above-average DAI did not exceed 86 years of age.

Radial increment trajectories (Fig. 3) revealed distinct growth patterns between the two areas. Over a 100-year period, trees in PNT accumulated ~ 300 mm in CRI, while trees in RBT accumulated ~ 200 mm. Although individual variation indicated some cases of growth stabilization, the general trend in both areas was an ongoing increase in radial growth, suggesting that individuals had not yet reached stabilization even after 100 years of age.

A significant positive correlation between tree diameter and age was observed only in PNT ($r = 0.44$, $p = 0.05$). However, notable variability was observed both within and between areas. Trees with similar diameters may differ greatly in age, and vice versa (Fig. 4). For instance, in PNT, two trees aged 143 and 145 years had DBHs of 140 and 51 cm, respectively. In RBT, trees aged 39 and 41 years had DBHs of 115 and 16 cm. Additionally, individuals of the same age (e.g., 90 years) presented different DBHs between areas: 133 cm in PNT and 39 cm in RBT (Fig. 4).

Mean growth ring width trajectory showed that during the initial analysed period (1901–1940), PNT trees exhibited significantly higher growth rates than those in RBT (Fig. 5). Starting in the 1940s, average ring widths in both areas became more similar, eliminating the significant differences observed earlier. The mean growth ring width trajectories indicate a general trend toward relative stabilization from that period onward, with both areas converging to approximately 2.7 mm in mean ring width. During this period, PNT trees experienced a gradual decline in growth rates, while RBT trees showed a slight increase, leading to the convergence of both growth trajectories. From the 1990s onward, a decline in growth rates was observed, reflecting a similar pattern in both study areas.

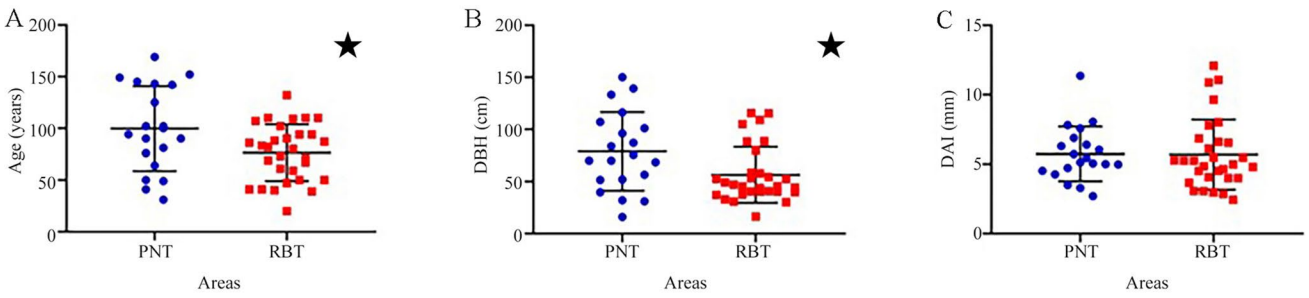


Fig. 2 Descriptive analysis of PNT and RBT populations. **A**: Boxplots of age, **B**: Diameter at breast height (DBH), and **C**: Diametric Annual Increment (DAI) of *Cedrela odorata* in the two study areas. The star indicates the parameters that showed statistical differences between the areas. PNT = Parque Nacional da Tijuca; RBT = Reserva Biológica do Tinguá

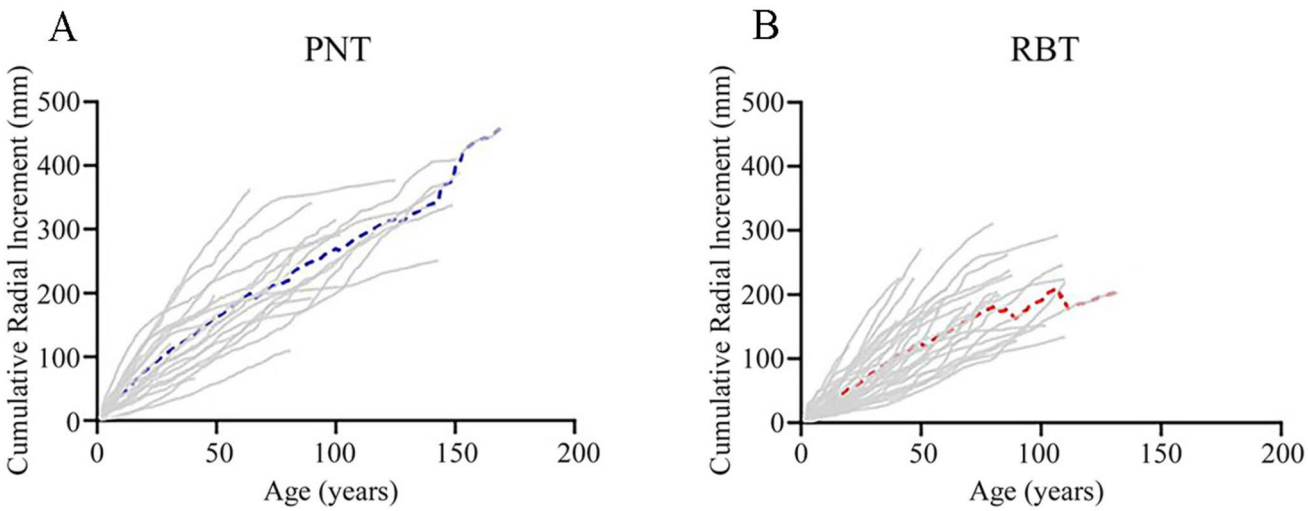


Fig. 3 Cumulative Radial Increment (CRI) for each individual analysed. **A**: PNT, **B**: RBT. Dashed line = average CRI of each study area

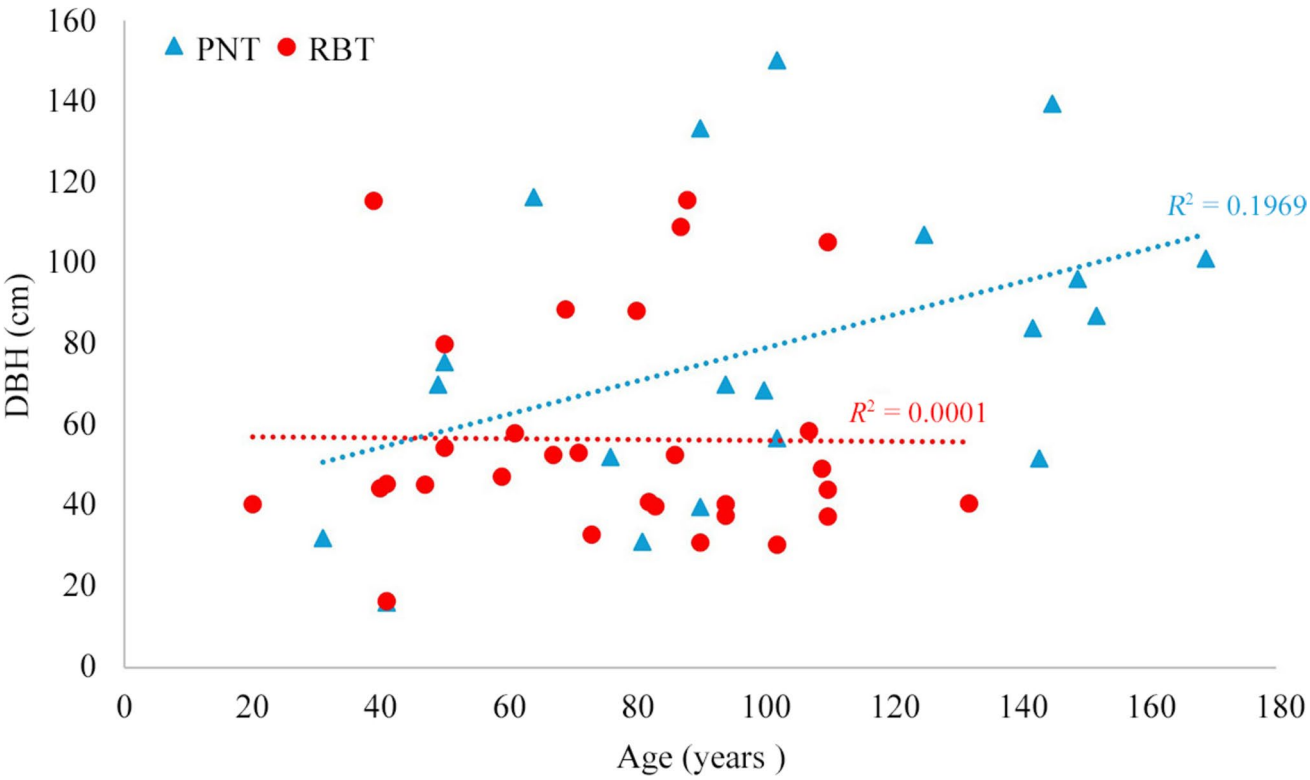


Fig. 4 Scatter plot of age versus diameter at breast height in the two study areas. Dotted lines = trend lines for each population

Discussion

The maximum ages recorded (169 for PNT and 132 for RBT) are consistent with the expected lifespan of tropical tree species, which typically reach around 200 years (Brienen et al. 2016). These results are linked to the historical protection of both areas, originally motivated by the water supply crisis during the Brazilian colonial period.

In general, trees in PNT exhibited greater ages and larger DBHs compared to those in RBT. However, mean DAI did

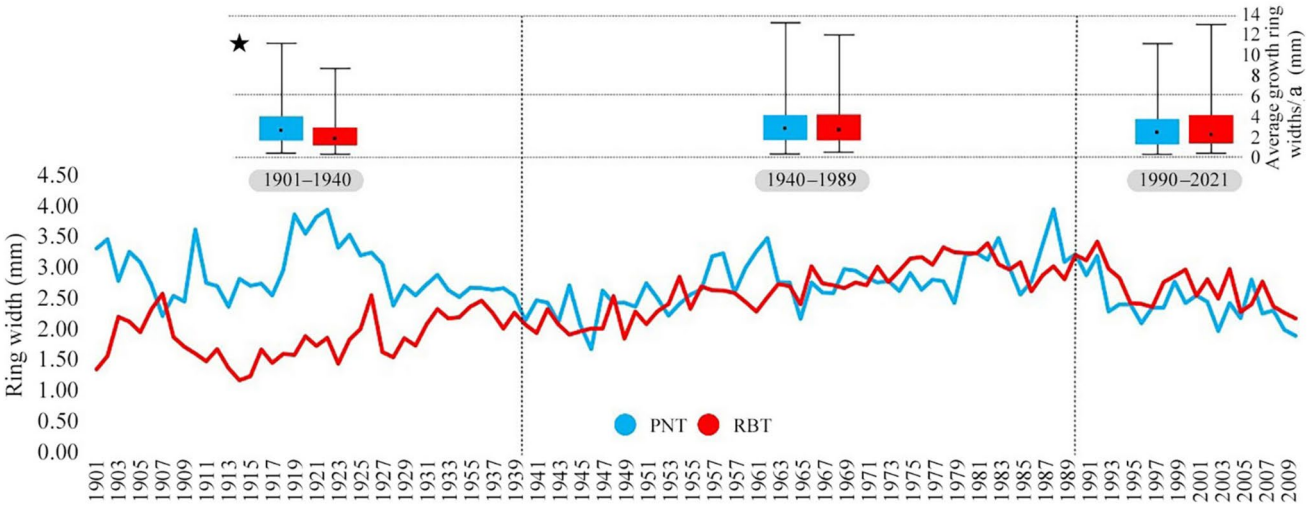


Fig. 5 Growth trajectories in PNT and RBT. Box plots shows average annual growth ring width measurements for each area during the periods 1901–1940, 1941–1989, and 1990–2010. The star represents a statistically significant difference between the study areas

not differ significantly between the study areas. Within each area, trees of similar age frequently showed wide variation in DBH, exceeding 100 cm in some cases, while individuals with similar DBHs sometimes differed by several decades in age. These discrepancies were also observed between areas: while younger trees (40–50 years) tended to have similar DBHs, older trees (> 90 years) in PNT often reached larger sizes. These findings highlight that DBH alone is not a reliable proxy for estimating tree age in *C. odorata*, reinforcing previous observations for other tropical species, particularly in the Atlantic Forest and similar biomes (Costa et al. 2013; Brienen et al. 2016; de Vasconcellos et al. 2016, 2019; da Costa et al. 2021; Fontana et al. 2024).

Evidence of intraspecific growth variability can be observed in the present dataset. For instance, in PNT, two 90-year-old trees had DAIs of 4.27 and 7.57 mm. In RBT, trees around 40 years old exhibited even greater differences, with DAI values ranging from 4 to 11.07 mm. This variation aligns with observations across tropical species (Worbes et al. 2003; Brienen et al. 2010; Groenendijk et al. 2014; Costa et al. 2015; Barbosa et al. 2018; Blagitz et al. 2019; López and Fontana 2024) and is influenced by factors such as nutrient availability, endogenous growth rhythms, and species-specific reproductive behaviors (Brienen et al. 2016; Baker et al. 2017; Costa et al. 2024). Additionally, growth release and suppression events, often triggered by changes in canopy structure, can cause variations in individual growth trajectories, further contributing to the observed heterogeneity (Brienen and Zuidema 2006; Schöngart et al. 2017; Xavier et al. 2021).

In PNT, the highest DBHs were observed in trees older than 90 years old, likely reflecting the influence of silvicultural interventions implemented in the mid-nineteenth century. These included regular planting spacing in parallel and perpendicular rows, land preparation, clearing of wild vegetation, successive cleanings after tree planting, routine plant care, and replacement of dead individuals (Brasil 1861). Such practices may have reduced early competition and improved seedling access to light, nutrients, and water, which are important resources for *Cedrela*, a light-demanding genus with high nutrient requirements (Dünisch et al. 2002). Additionally, proximity of seedlings to headwaters may have guaranteed consistent water availability during establishment. Together, these conditions likely enhanced early growth and long-term diameter expansion (da Silva Sales and Guedes-Bruni 2018, 2023; Brancalion et al. 2019). Studies conducted on *C. odorata* in the Amazon reinforce these findings, indicating significant diameter growth in seedlings subjected to silvicultural interventions, such as fertilization and periodic cleaning (Keefe et al. 2009; de Souza et al. 2010; Vieira et al. 2018). Such practices improve growth performance by reducing competition and enhancing resource availability, supporting our interpretation that the silvicultural care provided in PNT contributed to the growth patterns observed in older individuals.

Conversely, in RBT, the absence of active forest management allowed natural successional processes to shape forest dynamics. In these conditions, the forest's regenerative structure results in a dynamic population where trees compete for resources at different developmental stages, in various successional phases. This environmental filtering process allows species to succeed or fail naturally (Costa et al. 2015; Brienen et al. 2016; de Vasconcellos et al. 2019; López and Fontana 2024). These processes explain the initially lower growth rates in RBT compared to PNT, particularly during the early decades of trees establishment.

Despite the initial differences, growth trajectories in both areas converged over time. From the 1940s onward, average ring widths in PNT declined, while those in RBT increased slightly, resulting in similar growth rates. This convergence suggests that the planting carried out in PNT reached a more advanced successional stage without further silvicultural management, eventually reflecting competitive growth conditions similar to those in RBT since the beginning of the observation period. These trends align with the reduced woody growth observed in maturing forests, when competition intensifies and carbon is reallocated to functions such as reproduction, leaf and fine root production, and defence (Sánchez-Salguero et al. 2015; Anderson-Teixeira et al. 2022; Zhang et al. 2024).

Urbanization-related environmental changes may also influence tree growth dynamics, as increases in CO_2 concentration, rising temperatures, and altered precipitation patterns directly affect plant metabolism (Guimarães and Lee 2010; Baklanov et al. 2018; Locosselli and Buckeridge 2023). In Rio de Janeiro—Brazil's most urbanized metropolitan region (IBGE 2015)—these pressures are intensified by urban heat islands, elevated air and soil pollution, and high ozone concentrations that often exceed national and international standards (INEA 2020; Singh et al. 2021).

These environmental pressures have already been linked to alterations in functional and structural traits in native woody species growing in Rio de Janeiro (de Vasconcellos et al. 2017, 2019, 2025; de Vasconcellos and Callado 2020; de Almeida Bezerra et al. 2020, 2023; da Silva et al. 2023). Dendrochemical analyses revealed that urban trees accumulate higher concentrations of potentially toxic elements, such as sulphur and chlorine, with a marked increase since the 1980s (de Vasconcellos et al. 2025).

In our study, the decline in radial growth observed from the 1990s aligns with intensification of urban environmental stressors. This pattern reflects a broader global trend of growth decline in urban forests (Locosselli et al. 2019; Franceschi et al. 2023; Gao et al. 2023; Wu et al. 2025). *Cedrela odorata*, which is particularly sensitive to water availability, may be especially susceptible to urban-related stressors (Costa et al. 2013, 2024; Venegas-González et al. 2018; Granato-Souza et al. 2019; Menezes et al. 2022; Ortega Rodriguez et al. 2023). From the 1990's onward, individuals in RBT, situated ~ 50 km from the urban core, maintained higher growth rates than those in PNT—one of the biggest urban forests in the world -, reinforcing the interpretation that proximity to urban centres intensifies environmental constraints on tree growth.

Conclusion

This study provides the first assessment of long-term radial growth under active reforestation and natural regeneration within the same macroclimatic conditions and phytophysiognomic domain. The convergence in growth trajectories over time suggests that both strategies can support similar biomass accumulation, despite their different historical legacies. The wide age range and presence of young individuals demonstrate active recruitment and increasing structural complexity, reinforcing the species' resilience under different forest recovery pathways.

Tree rings in *C. odorata* serve as valuable environmental archives. They offer long-term insights into forest dynamics, responses to silvicultural interventions, successional stages, and environmental stressors. These findings underscore the relevance of dendroecological approaches in understanding forest development over extended timescales.

Future directions

Our findings offer practical insights for the planning and evaluation of forest restoration strategies. The early growth advantage of active reforestation and the long-term convergence with natural regeneration suggest that both approaches are viable, depending on restoration goals and timeframes. Active planting may be preferred when rapid biomass recovery is needed, while natural regeneration offers a cost-effective alternative that promotes long-term forest resilience.

Furthermore, tree-ring data proved to be a sensitive tool for detecting forest responses to past management and urban environmental pressures. Incorporating dendroecological monitoring into restoration programs can support adaptive management, enabling early detection of growth decline or shifts associated with urbanization, climate change, or site degradation. These insights can guide the development of site-specific restoration protocols and long-term monitoring frameworks.

Acknowledgements We would like to thank Monique Silva da Costa and Maxmira Arêdes-dos-Reis for granting access to the samples collected in RBT between 2010 and 2012, which were essential for the development of this work. We also extend our gratitude to Mário Tomazello-Filho and the Laboratório de Anatomia, Identificação e Densitometria de Raios X em Madeira (ESALQ/USP) for providing access to laboratory facilities and the use of the scanners, enabling the digitalization of the samples for analysis. We further acknowledge João Victor S. Castelar for his assistance with the sample collection. Our thaks also extend to the Laboratório de Anatomia Vegetal (LAV/UERJ) for research support and logistical assistance. This study was supported by Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ; grants E-6/210.288/2021 and 26/204.346/2024), by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq; PQ No. 309959/2025-0), and by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES; Finance Code 001). This paper is derived from the master's thesis of the first author.

Funding The Article Processing Charge (APC) for the publication of this research was funded by the Coordenação de

Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier: 00x0ma614).

Data availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Abreu M de A (ed) (1992) Natureza e sociedade no Rio de Janeiro. Prefeitura da Cidade do Rio de Janeiro, Secretaria Municipal de Cultura, Turismo e Esportes, Departmento Geral de Documentação e Informação Cultural, Divisão de Editoração, Rio de Janeiro (in Portuguese)

Alvares CA, Stape JL, Sentelhas PC, de Moraes Gonçalves JL, Sparovek G (2014) Köppen's climate classification map for Brazil. Metz 22(6):711–728. https://doi.org/10.1127/0941-2948/2013/0507

Anderson-Teixeira KJ, Herrmann V, Rollinson CR, Gonzalez B, Gonzalez-Akre EB, Pederson N, Alexander MR, Allen CD, Alfaro-Sánchez R, Awada T, Baltzer JL, Baker PJ, Birch JD, Bunyavejchewin S, Cherubini P, Davies SJ, Dow C, Helcoski R, Kašpar J, Lutz JA, Margolis EQ, Maxwell JT, McMahon SM, Piponiot C, Russo SE, Šamonil P, Sniderhan AE, Tepley AJ, Vašíčková I, Vlam M, Zuidema PA (2022) Joint effects of climate, tree size, and year on annual tree growth derived from tree-ring records of ten globally distributed forests. Glob Change Biol 28(1):245–266. https://doi.org/10.1111/gcb.15934

Arêdes-dos-Reis M, Costa MS, Sasada-Sato CY, Callado CH (2016) Seasonal, multi-scale spatial and slope-oriented effects in cambial dynamics: an evaluation of sampling methods in *Cedrela odorata* (Meliaceae) in an Atlantic Forest area. Botany 94(10):993–999. https://doi.org/10.1139/cjb-2016-0082

Arêdes-dos-Reis M, Costa MS, dos Santos GUCA, Callado CH (2019) Sample size and cardinal orientation in cambial activity analysis: a case study. IAWA J 40(2):183–190. https://doi.org/10.1163/22941932-40190215

Baker JCA, Gloor M, Spracklen DV, Arnold SR, Tindall JC, Clerici SJ, Leng MJ, Brienen RJW (2016) What drives interannual variation in tree ring oxygen isotopes in the Amazon? Geophys Res Lett 43(22):11831–11840. https://doi.org/10.1002/2016gl071507

Baker JCA, Santos GM, Gloor M, Brienen RJW (2017) Does *Cedrela* always form annual rings? Testing ring periodicity across South America using radiocarbon dating. Trees 31(6):1999–2009. https://doi.org/10.1007/s00468-017-1604-9

Baklanov A, Grimmond CSB, Carlson D, Terblanche D, Tang X, Bouchet V, Lee B, Langendijk G, Kolli RK, Hovsepyan A (2018) From urban meteorology, climate and environment research to integrated city services. Urban Clim 23:330–341. https://doi.org/10.1016/j.uclim.2017.05.004

Barbosa ACM, Pereira GA, Granato-Souza D, Santos RM, Fontes MAL (2018) Tree rings and growth trajectories of tree species from seasonally dry tropical forest. Aust J Bot 66(5):414. https://doi.org/10.1071/bt17212

Blagitz M, Botosso PC, Longhi-Santos T, Bianchini E (2019) Tree rings in tree species of a seasonal semi-deciduous forest in southern Brazil: wood anatomical markers, annual formation and radial growth dynamic. Dendrochronologia 55:93–104. https://doi.org/10.1016/j.dendro.2019.04.006

Brancalion PHS, Holl KD (2016) Functional composition trajectory: a resolution to the debate between Suganuma, Durigan, and Reid. Restor Ecol 24(1):1–3. https://doi.org/10.1111/rec.12312

Brancalion PHS, Campoe O, Mendes JCT, Noel C, Moreira GG, van Melis J, Stape JL, Guillemot J (2019) Intensive silviculture enhances biomass accumulation and tree diversity recovery in tropical forest restoration. Ecol Appl 29(2):1–12. https://doi.org/10.1002/eap.1847

Brancalion PHS, Gandolfi S, Rodrigues RR (2015) Restauração florestal. Oficina de Textos, São Paulo. (in Portuguese)

Brasil (1861) Decreto No. 577 de 11 de dezembro de 1861

Brasil (1967) Decreto No. 60.183 de 8 de fevereiro de 1967

Brienen RJW, Zuidema PA (2005) Relating tree growth to rainfall in Bolivian rain forests: a test for six species using tree ring analysis. Oecologia 146(1):1–12. https://doi.org/10.1007/s00442-005-0160-y

Brienen RJW, Zuidema PA (2006) Lifetime growth patterns and ages of Bolivian rain forest trees obtained by tree ring analysis. J Ecol 94(2):481–493. https://doi.org/10.1111/j.1365-2745.2005.01080.x

Brienen RJW, Zuidema PA, Martínez-Ramos M (2010) Attaining the canopy in dry and moist tropical forests: strong differences in tree growth trajectories reflect variation in growing conditions. Oecologia 163:485–496. https://doi.org/10.1007/s00442-009-1540-5

Brienen RJW, Schöngart J, Zuidema PA (2016) Tree rings in the tropics: insights into the ecology and climate sensitivity of tropical trees. In: Tropical tree physiology. Springer International Publishing, pp 439–461. https://doi.org/10.1007/978-3-319-27422-5_20

Carlucci MB, Brancalion PHS, Rodrigues RR, Loyola R, Cianciaruso MV (2020) Functional traits and ecosystem services in ecological restoration. Restor Ecol 28(6):1372–1383. https://doi.org/10.1111/rec.13279

Conference of the Parties to the Convention on Biological Diversity (2022) Kunming-Montreal Global Biodiversity Framework

Costa MS, de Vasconcellos TJ, Barros CF, Callado CH (2013) Does growth rhythm of a widespread species change in distinct growth sites? IAWA J 34(4):498–509. https://doi.org/10.1163/22941932-00000040

Costa MS, Ferreira KEB, Botosso PC, Callado CH (2015) Growth analysis of five Leguminosae native tree species from a seasonal semidecidual lowland forest in Brazil. Dendrochronologia 36:23–32. https://doi.org/10.1016/j.dendro.2015.08.004

Costa MS, de Vasconcellos TJ, Lisi CS, Brandes AFN, Tomazello-Filho M, Callado CH (2024) Interrelationship between tree-ring width and supra-annual reproductive behaviour of *Cedrela odorata*: an alert for dendrochronological research. J Plant Ecol 17:rtad048. https://doi.org/10.1093/jpe/rtad048

da Silva Sales GP, Guedes-Bruni RR (2018) Um quebra-cabeça verde: "montando as peças" do reflorestamento empreendido na floresta da *Tijuca*. Fronteiras 7(3):58–77. https://doi.org/10.21664/2238-8869.2018v7i3. ((**in Portuguese**))

da Silva Sales GP, Guedes-Bruni RR (2023) New sources of biological data supporting environmental history of a tropical forest of southeastern Brazil. Historia Ambiental Latinoamericana y Caribeña (HALAC) Revista De La Solcha 13(2):281–308. https://doi.org/10.32991/2237-2717.2023v13i2.p281-308

da Costa WS, Da Cunha M, Macedo TM, de Andra Iguatemy M, Quinet A, Rodrigues PJFP, Barros CF (2021) Cambium phenology and dendrochronology of the endangered tropical tree *Ocotea catharinensis* Mez. IAWA J 42(2):111–120. https://doi.org/10.1163/22941932-bja10023

da Silva DB, de Vasconcellos TJ, Callado CH (2023) Effects of urbanization on the wood anatomy of *Guarea guidonia*, an evergreen species of the Atlantic Forest. Trees 37(1):99–110. https://doi.org/10.1007/s00468-020-02080-w

de Vasconcellos TJ, Callado CH (2020) Wood anatomy of *Ceiba speciosa* (A. St.-Hil.) Ravenna under urban pollution. IAWA J 41(1):30–47. https://doi.org/10.1163/22941932-00002109

de Almeida Bezerra L, Callado CH, Da Cunha M (2020) Does an urban environment affect leaf structure of *Eugenia uniflora* L. (Myrtaceae)? Acta Bot Bras 34(2):266–276. https://doi.org/10.1590/0102-33062019abb0329

de Almeida Bezerra L, Callado CH, Vasconcellos TJ, dos Santos Nogueira TOC, dos Santos RS, de Moreira Lima D, de Mattos JCP, dos Anjos MJ, Murata MM, Da Cunha M (2023) Chemical and cytotoxical changes in leaves of *Eugenia uniflora* L., a medicinal plant growing in the fourth largest urban centre of Latin America. Trees 37(1):85–98. https://doi.org/10.1007/s00468-021-02217-5

de Souza CR, de Azevedo CP, Lima RM, Rossi LMB (2010) Comportamento de espécies florestais em plantios a pleno sol e em faixas de enriquecimento de capoeira na Amazônia. Acta Amaz 40(1):127–134. https://doi.org/10.1590/s0044-59672010000100016

de Vasconcellos TJ, Costa MS, Barros CF, Da Cunha M, Callado CH (2016) Growth dynamics of *Centrolobium robustum* (Vell.) Mart. ex Benth. (Leguminosae-Papilionoideae) in the Atlantic Forest. Braz J Bot 39(3):925–934. https://doi.org/10.1007/s40415-016-0292-9

de Vasconcellos TJ, Da Cunha M, Callado CH (2017) A comparative study of cambium histology of *Ceiba speciosa* (A. St.-Hil.) Ravenna (Malvaceae) under urban pollution. Environ Sci Pollut Res Int 24(13):12049–12062. https://doi.org/10.1007/s11356-015-6012-3

de Vasconcellos TJ, Tomazello-Filho M, Callado CH (2019) Dendrochronology and dendroclimatology of *Ceiba speciosa* (A. St.-Hil.) *Ravenna* (Malvaceae) exposed to urban pollution in Rio de Janeiro city, Brazil. Dendrochronologia 53:104–113. https://doi.org/10.1016/j.dendro.2018.12.004

de Vasconcellos TJ, dos Santos RS, dos Anjos MJ, Tomazello-Filho M, Callado CH (2025) Recording chemical changes in an urban environment: a dendrochemical study of *Ceiba speciosa* (A. St.-Hil.) Ravenna (Malvaceae) in the Atlantic Forest. Dendrochronologia 89:126286. https://doi.org/10.1016/j.dendro.2024.126286

Dean W (1996) With broadax and firebrand: the destruction of the Brazilian Atlantic forest. University of California Press, Berkeley. https://doi.org/10.2307/20047336

Derhé MA, Murphy H, Monteith G, Menéndez R (2016) Measuring the success of reforestation for restoring biodiversity and ecosystem functioning. J Appl Ecol 53(6):1714–1724. https://doi.org/10.1111/1365-2664.12728

Drummond JA (1988) O jardim dentro da máquina: breve história ambiental da Floresta da Tijuca. Rev Estud Hist 1(2):276–298 ((**in Portuguese**))

Dünisch O, Bauch J, Gasparotto L (2002) Formation of increment zones and intraannual growth dynamics in the xylem of *Swietenia macrophylla*, *Carapa guianensis*, and *Cedrela odorata* (Meliaceae). IAWA J 23(2):101–119. https://doi.org/10.1163/22941932-90000292

Fontana C, López L, Santos GM, Villalba R, Hornink B, Assis-Pereira G, Roig FA, Tomazello-Filho M (2024) A new chronology of *Cedrela fissilis* (Meliaceae) for Southern Brazil: combining classical dendrochronology and radiocarbon dating. Dendrochronologia 85:126214. https://doi.org/10.1016/j.dendro.2024.126214

Forman LL, Pennington TD, Styles BT (1975) A generic monograph of the Meliaceae. Blumea: Biodiversity. Evol Biogeogr Plants 22(3):419–540. https://doi.org/10.2307/4110009

Franceschi E, Moser-Reischl A, Honold M, Rahman MA, Pretzsch H, Pauleit S, Rötzer T (2023) Urban environment, drought events and climate change strongly affect the growth of common urban tree species in a temperate city. Urban For Urban Green 88:128083. https://doi.org/10.1016/j.ufug.2023.128083

Gao XH, Zhao BQ, Chen ZC, Song WQ, Li ZS, Wang XC (2023) The impact of urbanization on tree growth and xylem anatomical characteristics. Biology 12(11):1373. https://doi.org/10.3390/biology12111373

Gatica-Saavedra P, Echeverría C, Nelson CR (2017) Ecological indicators for assessing ecological success of forest restoration: a world review. Restor Ecol 25(6):850–857. https://doi.org/10.1111/rec.12586

Gentry AH (1988) Changes in plant community diversity and floristic composition on environmental and geographical gradients. Ann Mo Bot Gard 75(1):1–34

Granato-Souza D, Stahle DW, Barbosa AC, Feng S, Torbenson MCA, de Assis Pereira G, Schöngart J, Barbosa JP, Griffin D (2019) Tree rings and rainfall in the equatorial Amazon. Clim Dyn 52(3–4):1857–1869. https://doi.org/10.1007/s00382-018-4227-y

Groenendijk P, Sass-Klaassen U, Bongers F, Zuidema PA (2014) Potential of tree-ring analysis in a wet tropical forest: a case study on 22 commercial tree species in Central Africa. For Ecol Manage 323:65–78. https://doi.org/10.1016/j.foreco.2014.03.037

Guimarães LE, Lee F (2010) Levantamento do perfil e avaliação da frota de veiculos de passeio brasileira visando racionalizar as emissões de dióxido de carbono. Soc Nat 22(3):577–592. https://doi.org/10.1590/s1982-45132010000300013

Higgs ES (2003) Nature by design: people, natural process, and ecological restoration. MIT Press, Cambridge

IBAMA (2006) Plano de Manejo da Reserva Biológica do Tinguá (in Portuguese)

IBGE (2015) Síntese de indicadores sociais: uma análise das condições de vida da população brasileira. Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro ((**in Portuguese**))

ICMBio (2008) Plano de Manejo do Parque Nacional da Tijuca. (in Portuguese)

INEA (2020) Instituto Estadual do Ambiente: Relatório da qualidade do ar do Estado do Rio de Janeiro: ano base 2018. Instituto Estadual do Ambiente, Rio de Janeiro, Brazil. (in Portuguese). https://www.inea.rj.gov.br/wp-content/uploads/2020/11/relatorio-qualidade-ar-2018.pdf

INPE (2022) Relatório Anual de Desmatamento – RAD

IUCN (2017) *Cedrela odorata*: Mark, J. & Rivers, M.C.: The IUCN Red List of Threatened Species 2017: e.T32292A68080590

Keefe K, Schulze MD, Pinheiro C, Zweede JC, Zarin D (2009) Enrichment planting as a silvicultural option in the eastern Amazon: case study of Fazenda Cauaxi. For Ecol Manage 258(9):1950–1959. https://doi.org/10.1016/j.foreco.2009.07.037

Leitão IAC, da Silva Sales GP, da Silva Nunes R, Guedes-Bruni RR (2023) Transformação da paisagem nas serranias do tinguá e arredores da Baía de guanabara: história ambiental, biodiversidade e recursos Hídricos. Fronteiras 11(4):113–133. https://doi.org/10.21664/2238-8869.2022v11i4.p113-133. ((**in Portuguese**))

Lisi CS, Pagotto MA, Anholetto CR Jr, Nogueira FC Jr, Santos HL, Costa CM, Menezes ÍRN, Roig Juñet FA, Tommasiello Filho M (2020) Dendroecological studies with *Cedrela odorata* L., northeastern Brazil. In: Latin American dendroecology. Springer International Publishing, pp 37–59. https://doi.org/10.1007/978-3-030-36930-9_3

Locosselli GM, Buckeridge MS (2023) The science of urban trees to promote well-being. Trees 37(1):1–7. https://doi.org/10.1007/s00468-023-02389-2

Locosselli GM, de Camargo EP, Moreira TCL, Todesco E, de Fátima Andra M, de André CDS, de André PA, Singer JM, Ferreira LS, Saldiva PHN, Buckeridge MS (2019) The role of air pollution and climate on the growth of urban trees. Sci Total Environ 666:652–661. https://doi.org/10.1016/j.scitotenv.2019.02.291

López L, Fontana C (2024) A cross-biome analysis of *Cedrela fissilis* Vell: growth, age, and diameter class transitions. Trees For People 18:100666. https://doi.org/10.1016/j.tfp.2024.100666

Loureiro N, Mantuano D, Manhães A, Sansevero J (2023) Use of the trait-based approach in ecological restoration studies: a global review. Trees 37(5):1287–1297. https://doi.org/10.1007/s00468-023-02439-9

Marques MCM, Grelle CEV (2021) The Atlantic forest: history, biodiversity, threats and opportunities of the mega-diverse forest. Springer International Publishing, Berlin. https://doi.org/10.1007/978-3-030-55322-7

Menezes IRN, Aragão JRV, Pagotto MA, Lisi CS (2022) Teleconnections and edaphoclimatic effects on tree growth of *Cedrela odorata* L. in a seasonally dry tropical forest in Brazil. Dendrochronologia 72:125923. https://doi.org/10.1016/j.dendro.2022.125923

Netherlands Environmental Assessment Agency (2020) Goals and Commitments for the Restoration Decade

Ortega Rodriguez DR, Sánchez-Salguero R, Hevia A, Granato-Souza D, Cintra BBL, Hornink B, Andreu-Hayles L, Assis-Pereira G, Roig FA, Tomazello-Filho M (2023) Climate variability of the southern Amazon inferred by a multi-proxy tree-ring approach using *Cedrela fissilis* Vell. Sci Total Environ 871:162064. https://doi.org/10.1016/j.scitotenv.2023.162064

dos Reis BN, Nascimento MT (2024) Functional attributes in ecological restoration in tropical forests: strategies and perspectives. Rev Científica Multidiscip Núcleo Do Conhecimento 153–175. https://doi.org/10.32749/nucleodoconhecimento.com.br/biology/ecological-restoration-in-tropical

Ribeiro MC, Metzger JP, Martensen AC, Ponzoni FJ, Hirota MM (2009) The Brazilian Atlantic Forest: how much is left, and how is the remaining forest distributed? Implications for conservation. Biol Conserv 142(6):1141–1153. https://doi.org/10.1016/j.biocon.2009.02.021

Ribeiro MC, Martensen AC, Metzger JP, Tabarelli M, Scarano F, Fortin MJ (2011) The Brazilian Atlantic forest: a shrinking biodiversity hotspot. In: Biodiversity hotspots. Springer, pp 405–434. https://doi.org/10.1007/978-3-642-20992-5_21

Sánchez-Salguero R, Linares JC, Camarero JJ, Madrigal-González J, Hevia A, Sánchez-Miranda Á, Ballesteros-Cánovas JA, Alfaro-Sánchez R, García-Cervigón AI, Bigler C, Rigling A (2015) Disentangling the effects of competition and climate on individual tree growth: a retrospective and dynamic approach in Scots pine. For Ecol Manage 358:12–25. https://doi.org/10.1016/j.foreco.2015.08.034

Scarano FR, Ceotto P (2015) Brazilian Atlantic forest: impact, vulnerability, and adaptation to climate change. Biodivers Conserv 24(9):2319–2331. https://doi.org/10.1007/s10531-015-0972-y

Schöngart J, Bräuning A, Barbosa ACMC, Lisi CS, de Oliveira JM (2017) Dendroecological studies in the neotropics: history, status and future challenges. In: Dendroecology. Springer International Publishing, pp. 35–73. https://doi.org/10.1007/978-3-319-61669-8_3

da Silva Sales GP, Guedes-Bruni RR (2024) The planting of the first national forests in Brazil: forest policy and the emergence of tropical forestry in the nineteenth century. In: Environment & Society Portal. https://www.environmentandsociety.org/arcadia/planting-first-national-forests-brazil-forest-policy-and-emergence-tropical-forestry

Singh RB, Chatterjee S, Mishra M, de Lucena AJ (2021) Practices in regional science and sustainable regional development: experiences from the global south. Springer, Singapore. https://doi.org/10.1007/978-981-16-2221-2

Stefano MV, Calazans LSB, Sakuragui CM (2015) Meliaceae in Lista de Espécies da Flora do Brasil. http://floradobrasil2015.jbrj.gov.br/jabot/floradobrasil/FB9989

Tomazello Filho M, Botosso P, Lisi C (2000) Potencialidade da família Meliaceae para Dendrocronologia em regiões tropicais e subtropicais. Dendrocronología En América Latina Ediunc 2000:381–431 (**(in Portuguese)**)

United Nations (2020) The United Nations decade on ecosystem restoration strategy.

Venegas-González A, Roig FA, Lisi CS, Junior AA, Alvares CA, Tomazello-Filho M (2018) Drought and climate change incidence on hotspot *Cedrela* forests from the *Mata* Atlântica biome in southeastern Brazil. Glob Ecol Conserv 15:e00408. https://doi.org/10.1016/j.gecco.2018.e00408

Vieira SB, de Carvalho JOP, Gomes JM, da Silva JCF, Ruschel AR (2018) *Cedrela odorata* L. tem potencial para Ser utilizada na silvicultura pós-colheita na amazônia brasileira? Ciênc Florest 28(3):1230–1238. https://doi.org/10.5902/1980509833361

Worbes M (1999) Annual growth rings, rainfall-dependent growth and long-term growth patterns of tropical trees from the Caparo Forest Reserve in Venezuela. J Ecol 87(3):391–403. https://doi.org/10.1046/j.1365-2745.1999.00361.x

Worbes M, Staschel R, Roloff A, Junk WJ (2003) Tree ring analysis reveals age structure, dynamics and wood production of a natural forest stand in Cameroon. For Ecol Manage 173(1–3):105–123. https://doi.org/10.1016/S0378-1127(01)00814-3

Wu Q, Zaw Z, Yang JM, Yang RQ, Li ZS, Hauer RJ, Li HF, Fan ZX, Lu HC, Sterck F (2025) Urbanization associated with greater tree growth declines in urban than in rural forests. Urban For Urban Green 104:128599. https://doi.org/10.1016/j.ufug.2024.128599

Xavier CN, Granato-Souza D, Barbosa ACMC, da Silva JRM (2021) Tropical dendrochronology applied to invasive tree species in the Brazilian Atlantic Forest. J For Res 32(1):91–101. https://doi.org/10.1007/s11676-019-01075-9

Zappi DC, Filardi FLR, Leitman P et al (2015) Growing knowledge: an overview of Seed Plant diversity in Brazil. Rodriguésia 66:1085–1113. https://doi.org/10.1590/2175-7860201566411

Zhang HT, Ovaskainen O, Chi XL, Guo Q, Tang ZY (2024) Spatiotemporal variation in the negative effect of neighbourhood crowding on stem growth. J Ecol 112(5):1140–1149. https://doi.org/10.1111/1365-2745.14291

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.