The Influence of Rainfall and Temperature on Radial Growth of Urban Trees Under the Impact of Steel Industry Pollution

Thayanne Caroline Castor Neto,[a] José Luis Penetra Cerveira Lousada,[b] Cláudia Fontana,[c] Carolina Gomes Moreira,[d] and João Vicente de Figueiredo Latorraca [e,*]

The aim of this study was to analyze the growth rings and evaluate the effect of the urban environment on the growth of *Terminalia catappa* L. under intense industrial activity. At least two wood samples were obtained from each tree with an increment borer. The regions of Volta Redonda (Northwest and Southeast regions) and Resende (used as control) were established for the collection. The dendrochronological potential of *T. catappa* indicated sensitivity to precipitation and temperature in a more exposed urban and industrial steel pollution area because there were differences in growth when compared to an area less exposed to the same pollution. Thus, it was possible to conclude that this species has the potential to be used as a bioindicator of anthropogenic activities. In addition, the delimitation of the growth rings of the studied species contributes to the realization of future dendrochronological studies, expanding the understanding of the behavior of this species present in urban environments at different regional scales. This study reinforces the importance of rainfall and temperature in regulating radial growth in tropical forests.

DOI: 10.15376/biores.18.3.4771-4789

Keywords: Bioindicator; Tree rings; Tropical tree; Urban pollution

*Contact information: a: Postgraduate Program in Environmental and Forest Sciences, Federal Rural University of Rio de Janeiro, 23890-000, Seropédica, Rio de Janeiro, Brazil; b: Centre for the Research and Technology of Agro-Environmental and Biological Sciences (CITAB), University of Trás-os-Montes and Alto Douro, 5001-801, Vila Real, Portugal; c: Department of Forest Science, Luiz de Queiroz School of Agriculture, University of São Paulo, 13418-900, Piracicaba, São Paulo, Brazil; d: Department of Environmental Sciences, Federal Rural University of Rio de Janeiro, 23890-000, Seropédica, Rio de Janeiro, Brazil; e: Department of Forest Products, Federal Rural University of Rio de Janeiro, 23890-000, Seropédica, Rio de Janeiro, Brazil; *Corresponding author: latorraca@ufrrj.br*

INTRODUCTION

The study of growth dynamics of a woody species leads to a better understanding of specific strategies developed in favor of its adaptation in each environment. Trees react according to environmental variables, which may be reflected in the cambial activity and in the formation of annual rings, expressing events that occurred both in the past and in the present year (Tomazello Filho *et al*. 2001). Climate, for example, is considered one of the most important modulators of tree growth (Locosselli *et al*. 2019a), and in this sense, dendrochronology makes it possible not only to determine age, but also to study the performance of trees as a function of factors that made them grow (Fontana *et al*. 2018b), both in natural and urban environments.

In addition to climate, other variables can affect plant performance, especially those growing in urban environments that have less favorable environmental conditions. The trees that are present in these environments are exposed to thermal stress, soil drought, and low air humidity (Gillner *et al*. 2014). Therefore, these factors may contribute to the increased vulnerability of tree development (Locosselli *et al*. 2019a). A first step in predicting forest resistance and resilience to unfavorable conditions is to know how it performed in relation to past climatic conditions. To investigate this issue by dendrochronological methods, it is necessary to identify which species are sensitive to the environmental conditions to the point of influencing annual growth rings. In this context, one of the authors' goals was to explore the dendrochronological potential of and assess climate influence on radial growth in *Terminalia catappa* L. (almond tree), growing in urban conditions. The aim was to evaluate the potential of *T. catappa* as an environmental bioindicator. Furthermore, atmospheric pollution, linked to the urban environment, is considered one of the most important environmental concerns (Volná *et al*. 2021). The presence of steel industries in urban areas can significantly increase air pollution by emitting toxic heavy metals such as lead, cadmium, mercury, arsenic, chromium, and nickel, as well as various air pollutants such as acid gases (SO_2 and NO_X), incomplete combustion pollutants (CO and HC), and particulate matter (PM) of varying sizes (Wang *et al*. 2016), which can alter the optical properties of leaf surfaces, leading to a reduction in the amount of light required for photosynthesis (Prajapati 2012). Because it is a critical problem for human health, the monitoring of these pollutants has become essential during urbanization (Isinkaralar 2022).

Considering the sensitivity of species when recording changes in the environment, dendrochronological studies have been conducted to observe the effect of atmospheric pollution on the growth of tree species (Battipaglia *et al*. 2010; Bartens *et al*. 2012; Gillner *et al*. 2014; Sensuła *et al*. 2017; Kukarskih *et al*. 2022). Gillner *et al*. (2014) affirm that tree-ring analyses are a valuable tool for urban forestry to assess the capability of tree species to withstand future climatic conditions that are aggravated in urban heat islands and help in the selection of adapted plantations. The same authors found that two important species of urban forestry in the city of Dresden, in Germany, *Acer platanoides* L., and *Acer pseudoplatanus* L., should be planted at urban sites with lower heat and drought stress. Sensula *et al*. (2017), studying *Pinus sylvestris* L. growing near sites of chemical factories in Poland, discovered that the effects of industrial pollution have been recorded by this pine species *via* the long-term reduction in the size of thickness growth, reduction in the level of homogeneity of short-term incremental response, and reduced susceptibility of trees to short-term environmental impulses. The authors concluded that pollution could affect the size of incremental growth and disturbance in the incremental reaction of trees. Kukarskih *et al*. (2022) after studying *P. sylvestris* in Russia concluded that environmental pollution negatively affects tree growth. Moreover, the results of climate and historical data analysis suggest that the trees on urban sites were weakened by both climate and air pollution factors after 1941 because of the introduction of more than 60 industrial factories to the studied city, which generated a significant increase in air pollution.

In Brazil, there are still few studies that address the same effect on urban trees (Chagas 2013; Geraldo *et al*. 2014; Locosselli *et al*. 2019; Vasconcellos *et al*. 2019). For example, Chagas (2013) studied the species *Tabebuia pentaphylla* Hemsley and *Poincianella pluviosa* (DC.) Queiroz and discovered that changes in the pattern of climatic response can provide evidence regarding the influence of non-climatic factors, such as stress and sources of pollution, on the annual growth rate of trees in urban and peri-urban locations. Locosselli *et al*. (2019) used *Tipuana tipu* (Benth.) Kuntze to assess how climate and air pollution affect the development of urban trees and found that climate modulates the growth of these trees in the urban environment. However, the authors also concluded that air pollution has a dramatic influence on tree inter-annual growth variability compared to climate and may be considered a limitation to tree growth. Vasconcellos *et al*. (2019) found that there is an immediate response of the species *Ceiba speciosa* (A.St.-Hil., A.Juss. & Cambess.) Ravenna in urban environments in relation to the rainfall and the dry and hot climate, and the absence of natural water reserves in urban soil may explain this more immediate response of urban tree growth to rainfall and temperature indexes. Therefore, the search for varied species can add to the knowledge base and expand the performance of studies on this topic in the country.

In this context, *T. catappa*, an exotic but quite common species, is found in most cities in Brazil, especially in urban areas (Ribeiro *et al*. 2020). However, questions remain regarding the growth dynamics of this species in an urban environment and how exposure to atmospheric pollution can interfere with the formation of rings in these environments. Therefore, the present study aimed to analyze the effect of the urban, industrial environment on growth rings of *T. catappa*. Knowing that this species has dendrochronological potential (Chagas 2009), it is expected to find differences in growth and responses to climatic conditions because of interference from atmospheric pollution. Thus, because it is a consolidated species in urban afforestation, the study of its growth dynamics in an anthropic environment can contribute to future studies being conducted at different regional scales.

EXPERIMENTAL

Study Areas

The study was conducted in the municipalities of Volta Redonda (22º31'23" S, 44º06'15" W) and Resende (22°27'46” S, 44°27'20” W), the latter being for the purpose of controlling the samples, as it is approximately 40 km away from an imposing steel industry in Volta Redonda. Both are in the Middle Paraíba do Sul region, in the state of Rio de Janeiro, Brazil. The altitude in Volta Redonda ranges from 363 m to 707 m a.n.m. on the banks of the Paraíba do Sul River, while in the main area it is 380.3 m (Gioda *et al*. 2004). According to the Köppen climate classification, the climate is Cwa (humid subtropical zone, with dry winters and hot summers) (Alvares *et al*. 2013). The average annual precipitation is 1,337 mm and the average temperature is 21 °C (Rocha and Guimarães 2017). February is the hottest month (24 °C), and July is the coldest (17 °C) (Montine *et al*. 2014). The dry season is from April to September and the wet season is from October to March.

Sampling and Tree Ring Measurements

Initially, a survey of individuals of *T. catappa* present in the surroundings of the steel mill was conducted, within a radius of 2500 m from the industrial plant. Two regions were also established for collection (Northwest and Southeast) considering the pollution levels in the municipality and the predominant wind direction. Located on the west side of the Paraíba do Sul River, the northwest region exhibits higher levels of pollution, while the southeast region, located on the east side of the same river, has lower levels (Peiter and Tobar 1998). The predominant wind direction is northwestward, according to a survey of data made available by State Institute of the Environment (INEA) between 2001 and 2018. Of the 110 individuals of *T. catappa* found and georeferenced in Volta Redonda, 86 trees were in good phytosanitary condition and were chosen for the accomplishment of this study: 40 in the southeast region and 35 in the northwest region. In Resende, 11 trees were sampled (used as control, because they were approximately 40 km from the steel factory). The study areas, the collection points, and the climate diagram are illustrated in Fig. 1.

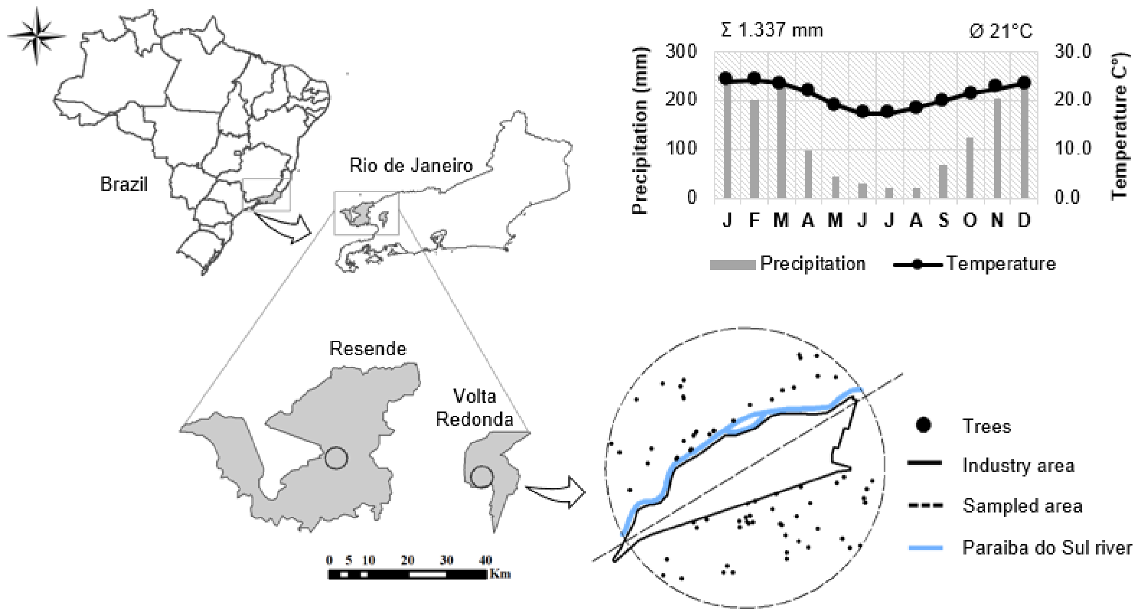

Fig. 1. Representation of study areas; Delimitation of the sampled area, the collection points, and a climatic diagram of the Resende meteorological station.

At least two wood samples, perpendicular to each other, were obtained from each tree using an increment borer in the bark-pith direction at 1.30 m above the ground. After collection, the samples were polished with a sequence of sandpaper (between 80 to 1200 grains/mm²) to highlight the transverse plane. The samples were scanned at 1200 dpi for analysis and counting of annual rings.

The width of the annual rings was measured using CooRecorder version 7.8 (Cybis Elektronik & Data AB, Saltsjöbaden, Sweden) with an accuracy of 0.01 mm in the digitized images. The COFECHA software was used to statistically verify the cross dating and the quality of the measurement of the rings (Holmes *et al*. 1986; Grissino-Mayer 2001), in which 30-year segments were used with 15-year overlaps. Then, the ARSTAN software was used to remove the biological age trend of individual series and adjust a common growth signal between the trees (Cook and Holmes 1996), therefore, the cubic smoothing spline model (50% of variance maintained in 20-year segments) was used to adjust each series. During this process, an individual series of rings was considered unreliable if it had a low correlation value with all other series and under these circumstances, that series was rejected to improve the common signal (Brienen and Zuidema 2005). Of a total of 172 cores, 38 cores were removed, 32 in the SE region and six in the NW region. No cores were removed from Resende. The chronologies were built with 134 cores.

Data Analysis and Statistics

At each site, the final mean chronology was constructed from the set of all standardized tree-ring width series for their populations. The standard chronology was used to perform Pearson's correlations, being the most sensitive to the signal of interest between growth and local climatic variables, both for the current and previous year, as well as for the dry and rainy season periods. For this purpose, monthly precipitation, and temperature data between 1961 and 2018 were used and obtained from the nearest meteorological station to the studied locations (Resende station). The data were obtained by the National Institute of Meteorology (INMET). In addition, to evaluate the properties of the chronologies (Cook *et al*. 1990), the average sensitivity, the correlation between the series, Running Bar (RBar), and the expressed population signal (EPS) (Fritts 1976; Speer 2010) were calculated (in COFECHA and ARSTAN) for each study site. Furthermore, the cumulated radial increment (CRI) was calculated by adding the measurements of each ring and the radial annual increment (RAI) was calculated by dividing the CRI by the number of rings, to verify the performance differences between the sites.

Before performing the statistical analyses, all quantitative results were evaluated for normality and homoscedasticity using the Shapiro-Wilk and Levene tests, respectively. Values that did not follow a normal distribution were submitted to logarithmic transformation. The results of the radial increments were compared with each other by Student's t test at a confidence level of 95%, following the recommendations of Zar (2010).

RESULTS AND DISCUSSION

Annual Rings Delimitation and Measurements

In the three study sites, the species *T. catappa* presented distinct annual rings, visible to the naked eye, delimited either by the formation of a thin line of marginal axial parenchyma, or by the confluence of the lozenge aliform paratracheal parenchyma and often associated with vessel alignment, fibrous zones, and slight differences in vessel diameter at the transition to the next ring.

The cumulated radial increment was similar among the population trees in the Volta Redonda regions and higher in the trees in Resende (Fig. 2). Trees in the northwest region exceeded the average value of 200 mm of increment accumulated at approximately 75 years old, while trees in the southeast region reached this value at an approximate age of 60 years. In Resende, trees aged between 60 and 65 years showed a cumulated increase of 200 mm. However, the longest-lived trees were mostly in the most polluted region (northwest), with ages estimated at up to 110 years. The trees in the southeast region were up to 104 years old and the youngest individuals were concentrated in Resende, with a maximum age of 95 years. It is also observed that the maximum average of the accumulated radial increment occurred in the trees of the northwest region, with 266.51 mm at 110 years. The southeastern region had trees with 282.73 mm at 100 years of age and the trees of Resende with 220.44 mm at 95 years of age.

The trees in the northwest region (n = 32) had a mean age of 50 years, radial annual increment (RAI) and, at 45 years old a cumulated radial increment (CRI) of 2.60 mm/year (SD ± 0.58) and 116.78 mm (SD ± 26.16), respectively. In the southeast region (n = 24), the trees had a mean age of 47 years, with an annual radial increment at 45 years old of 2.83 mm/year (SD ± 0.41) and a radial increment of 127.45 mm (SD ± 18.59). In Resende (n = 11), the trees had an average age of 59 years. The radial annual increment at 45 years old was 2.87 mm/year (SD ± 0.29), and the radial increment was 129.02 mm (SD ± 13.13). The values of the annual and radial increments, as well as the dendrometric values of the trees used in the present study, can be requested from the first author.

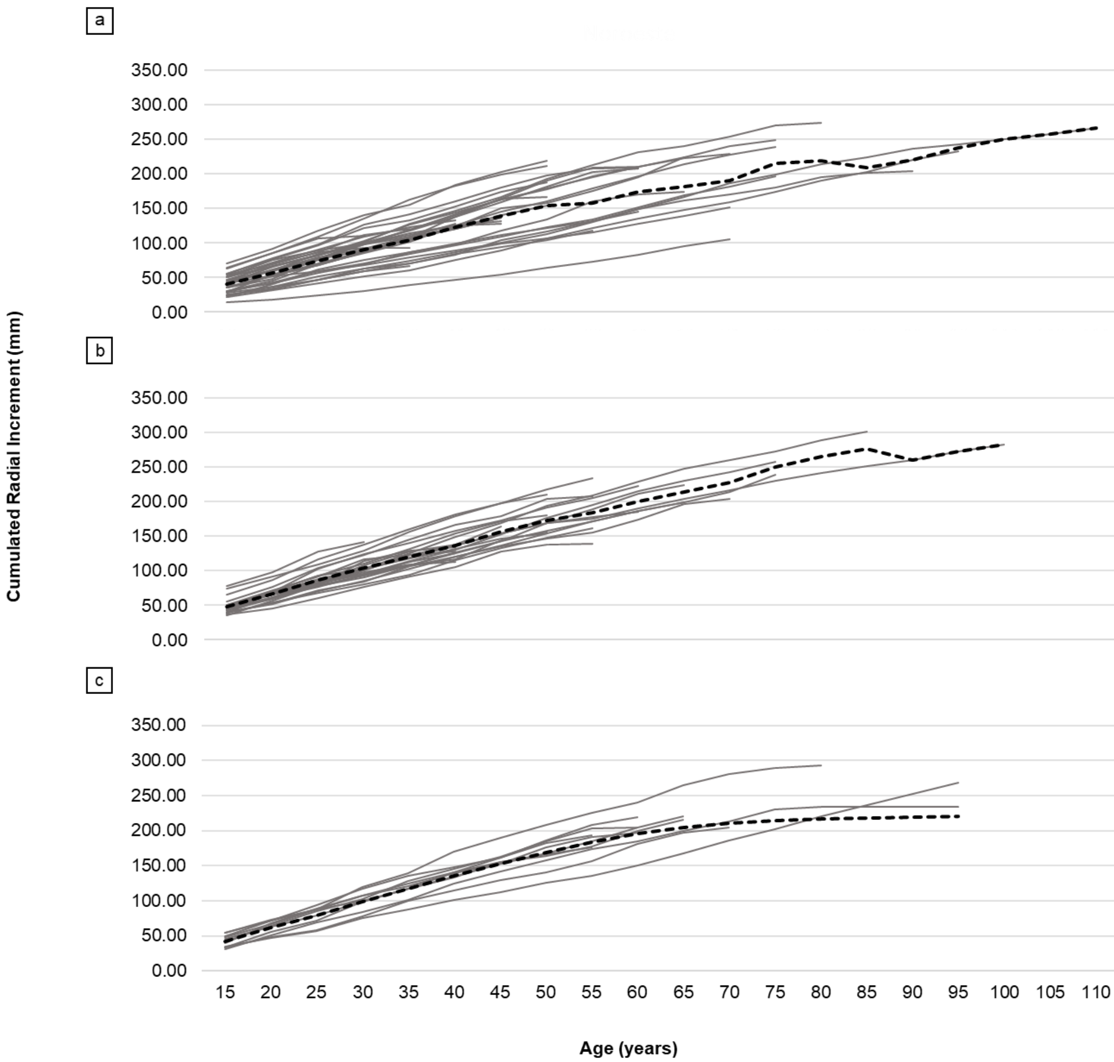

Fig. 2. Cumulated radial increment (CRI) of the *T. catappa* species in the study regions: (a) northwest, (b) southeast, and (c) Resende; the dashed line represents average growth.

Both the RAI and the CRI showed significant differences between the trees sampled in Volta Redonda and Resende. The RAI between the northwest region and Resende presented the following statistical values t = - 2.95, p = 0.008; between the southeast region and Resende presented t = - 2.58, p = 0.018. The CRI between the northwest region and Resende presented t = - 4.97, p = 0.000; between the Southeast region and Resende presented t = - 3.90, p = 0.000. However, between the northwest and southeast regions, there was no significant difference between tree growth. The RAI presented t = - 0.42, p = 0.679 and CRI presented t = - 1.34, p = 0.186.

Dendrochronological Analysis

After analyzing the growth rings, it was observed that from a total of 172 samples obtained from 86 trees (35 in the northwest region, 40 in the southeast region, and 11 in Resende), 134 radial samples were used to build the chronology (64 in the region north-west, 48 in the southeast, and 22 in Resende) (Table 1).

Table 1. Statistical Characteristics of the *T. catappa* Species in the Study Sites

Variables	Volta Redonda		Resende
	NW	SE	
Dated Trees / Radial Samples	32/64	24/48	11/22
Radial Annual Increment ± SD (mm)	2.80 ± 0.49	2.96 ± 0.40	3.50 ± 0.48
Period	1909-2019 (111 years)	1916-2019 (104 years)	1925-2019 (95 years)
Average Series Length (years)	50; SD = ±17 (Min = 26; Max = 111)	48; SD = ±16 (Min = 27; Max = 104)	60; SD = ±15 (Min = 35; Max = 95)
Average Sensitivity	0.504	0.519	0.482
Intercorrelation series	0.292	0.298	0.535
Rbar ± SD	0.123 ± 0.198	0.132 ± 0.195	0.265 ± 0.145
EPS	0.926	0.902	0.917

SD: Standard deviation; Min = minimum value; Max = maximum value; Rbar: Correlation coefficient; EPS: Expression of population sign.

The statistical characteristics, presented in Table 1, show that the mean sensitivity values were about 0.40 for the samples from the three study sites. The intercorrelation values of the series were similar for trees from Volta Redonda (northwest and southeast regions) (< 0.30); however, Resende presented a higher value (> 0.50). The values obtained for the variable Rbar varied between 0.123 and 0.265. The population expression signal (EPS) was high in all regions and ranged from 0.902 to 0.926 between study sites.

Figure 3 illustrates the growth rates of rings constructed from the standardized values, as well as the number of samples used during the analyzed period (1909 to 2019) at the study sites. The EPS and Rbar values were highlighted at an interval of 20 years (1950, 1970, 1990, and 2010), and it was found that, for all study sites, the EPS value increased as the number of radial samples increased. The correlation coefficient (Rbar) was higher in the period of 1950 and lower in the year of 1990 for the chronologies of the trees in the northwest region and Resende; and higher in the period of 2010 and lower in the period of 1950 for the chronologies of trees in the Southeast region.

The correlation indices of the width of the rings of the individuals analyzed in the northwest region (NW) are represented in Fig. 4. For the rainfall variable, there was a significant positive correlation in the current year; however, the significance occurred in two months of the dry season (July and September) and one month of the rainy season (October). In other words, the trees in the NW region showed a rapid response to the precipitation rates that occurred in the current year (Fig. 4a). For the temperature variable, there was only a significant negative correlation during the current year, in the month of October, which corresponds to the rainy season (Fig. 4b). In other words, wetter early spring and milder temperatures favor the growth of the species. For the Southeast (SE) region, there was no significant correlation between growth and climatic variables. In Resende, there was no significant correlation for the rainfall variable; however, for the temperature variable, there was a significant negative correlation for the month of September, referring to the previous month, which corresponds per month of the dry season.

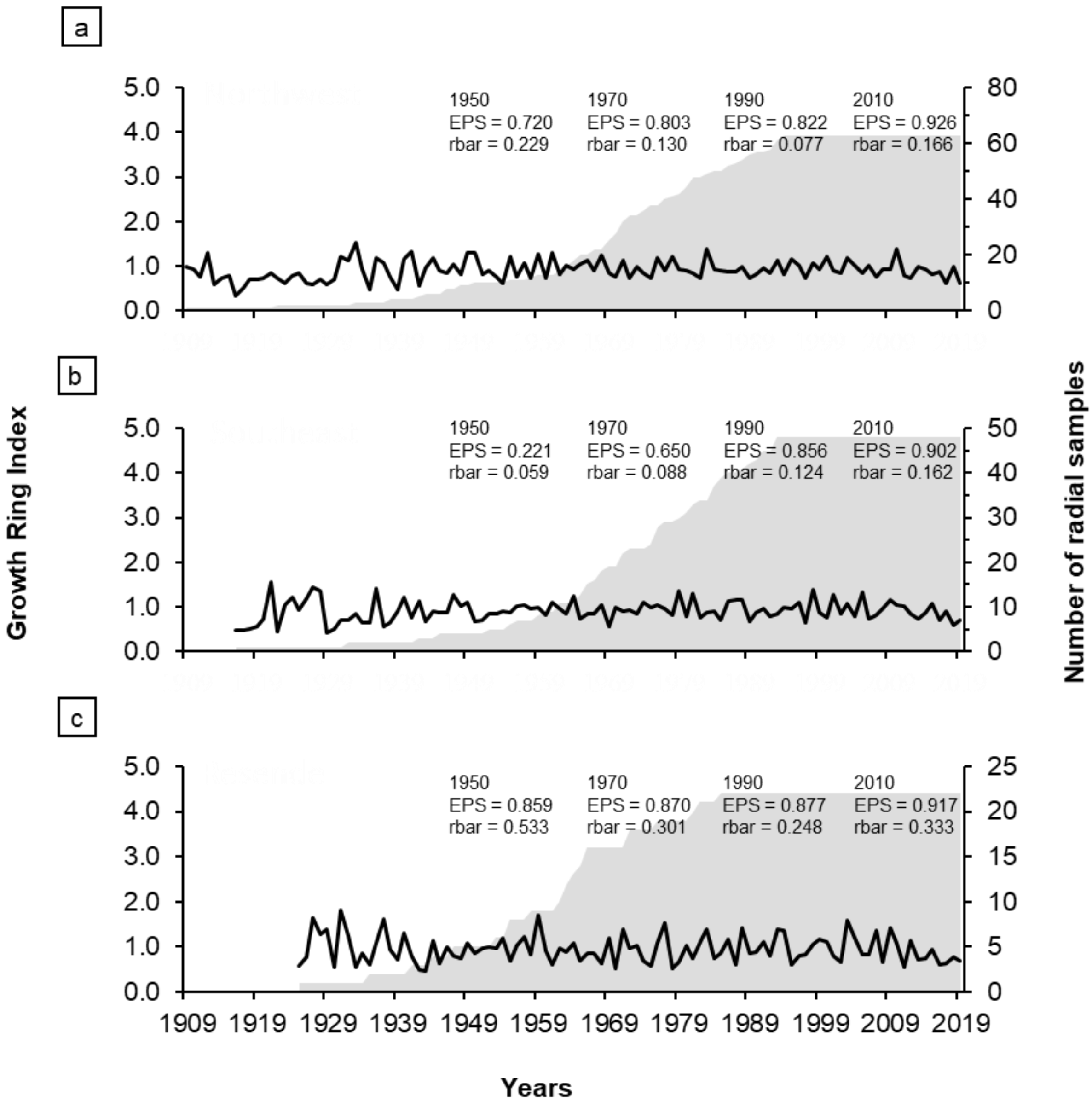

Fig. 3. The growth index of *T. catappa* rings in the study regions (black line): (a) northwest, (b) southeast, and (c) Resende. The gray area shows the number of radial samples used during the analysis period (1909 to 2019).

Considering the dendrochronological potential of the tropical species *T. catappa* (Chagas 2009), it was possible to describe a new analysis of the annual rings of this species, finding differences in growth and responses to climatic conditions in an environment under intense urban and steel activity. Although *T. catappa* is abundantly found in anthropic environments (Ribeiro *et al*. 2020), there are still few studies that address the characteristics of the wood of this species (Van Vliet 1979; Ruwanpathirana 2014), or even the analysis of rings (Chagas 2009).

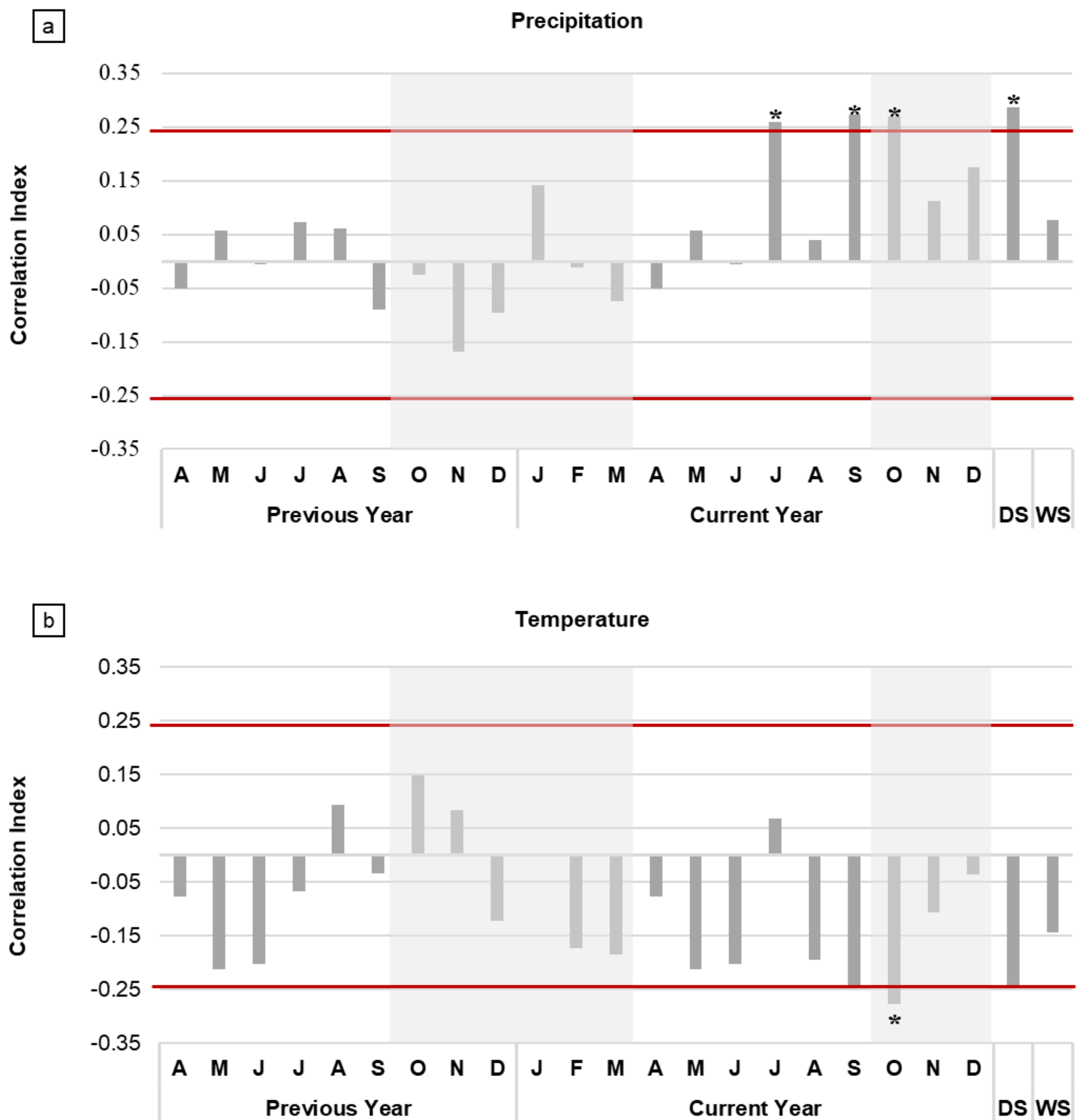

Fig. 4. Correlations between the width of *T. catappa* rings and climatic variables (1961 to 2018). The bars represent the correlation indices between the growth of the species in the northwest region and the indices of precipitation (a) and temperature (b). The light gray areas show the rainy season period. DS: Dry season; WS: Wet season. *Significant correlation values, critical correlation value = 0.259, for $p < 0.05$.

Some species of the genus *Terminalia* have distinct rings, such as *T. bellirica* (Gaertn.) Roxburgh, *T. myriocarpa* Van Heurck & Müll.Arg., *T. ivorensis* A. Chev, *T. superba* Engl. & Diels, *T. gracilipes* Capuron, *T. Amazonia* Exell in Pulle, and *T. oblonga* Steud. (Urbinati *et al*. 2003; Ridder *et al*. 2013; Singh *et al*. 2013; Gaspard *et al*. 2018; Marcelo-Peña *et al*. 2020). When studying the wood anatomy of several species of the Combretaceae family, Van Vliet (1979) described that the annual rings are distinct for *T. catappa*. A more recent study by Chagas (2009) reported a similar description, but detailed some more features, stating that the growth layers are distinctly demarcated by a thin band of marginal parenchyma, sometimes associated with confluent paratracheal axial parenchyma, by the thickening and radial flattening of the fiber wall. Additionally, there are observed variations in the diameter of the vessels in the transition of the annual rings. In other words, the description made by the author corroborates the macroscopic characteristics observed in the present study. Therefore, it is understood that *T. catappa* did not present differences in the forms of delimitation of the annual rings in an urban environment.

In dendrochronological studies of tropical species, the difficulty in delimiting annual rings is a frequent problem (Trouet *et al*. 2010; Ridder *et al*. 2013). For this reason, Brienen and Zuidema (2005) recommend the use of trunk discs to facilitate the verification of the discontinuity of rings in these species. In addition, anatomical characterization helps to correctly identify rings during measurements and reduces errors caused by false rings, which are a common feature in tropical species (Aragão *et al*. 2019), increasing the accuracy of measurements and favoring the construction of reliable chronologies (Fritts 1976; Vaganov *et al*. 2011; Brienen *et al*. 2016; López and Villalba 2020). In the present study, the level of difficulty in identifying the rings of *T. catappa* was high and demanded immense attention during this process, because the species present several forms of ring delimitation. Moreover, it was not possible to obtain an entire disc of the trunk once the samples came from urban afforestation.

The chronologies constructed with the 67 trees of *T. catappa* indicate that the success of cross-dating between individuals occurred due to a similar variation in growth patterns (Stahle *et al*. 1999). Some authors, working with species of the same genus, found average sensitivities that ranged from 0.64 for *T. gracilipes*, in a xerophytic environment in southwestern Madagascar, and 0.16 for *T. superba*, in lowland tropical forests in the western and in the central African continent (Ridder *et al*. 2013; Gaspard *et al*. 2018). Speer (2010) suggests that 0.20 is an accepted value in series that are sensitive enough for climate reconstruction. However, for trees present in urban environments, some authors found values greater than 0.40 (Chagas 2013; Locosselli *et al*. 2019; Vasconcellos *et al*. 2019), which is a value considered so sensitive that it may mean that dating is complicated by the frequent presence of narrow or absent rings close to wider rings (Speer 2010). However, the average sensitivities found for urban trees of *T. catappa* demonstrate year-to-year growth variability and a high common signal, inferring that the growth of trees from Volta Redonda and Resende can be influenced by an environmental, climatic, or non-climatic factor. The average correlation coefficient for all pairs of series described by the value of Rbar, in general, was low for the chronologies of the species *T. catappa* but like those found for urban trees (Locosselli *et al*. 2019; Vasconcellos *et al*. 2019). Furthermore, the correlations varied along the growth of the trees in the different studied places, which makes it possible to assess the period in which growth limitations occurred (Fritts 1976).

The EPS values express the quality that a finite set of radial samples must represent the chronology of the infinite population (Buras 2017); that is, the EPS value is influenced by the size of the sample set (Wigley *et al*. 1984; Speer 2010; Mérian *et al*. 2013). According to Buras (2017), the EPS value has been misinterpreted in dendrochronological studies, because the constant arbitrary use of the theoretical threshold above 0.85, suggested by Wigley *et al*. (1984), refers to the signal strength of the subsample, not the total sample size. Therefore, no specific EPS value can guarantee that the chronology of the growth rings is suitable for climatic reconstructions (Cook *et al*. 1990; Buras 2017).

Response of *Terminalia catappa* to Climate Conditions

In species from temperate climates, it is consensual to admit that the climate can significantly influence the tree radial growth (Fritts 1976; Holmes *et al*. 1986;

Schweingruber 1988; Speer 2010; Vaganov *et al*. 2011). Nevertheless, the use of tropical species in dendrochronological studies was for some time questioned, as some authors assumed that tropical species usually did not produce annual rings. However, the recent work by Zuidema *et al*. (2022), which brought together the contribution of 53 authors and was based on a new global network consisting of over 14,000 tree-ring data series from 350 locations across the tropics, makes it possible to identify the formation of annual rings in hundreds of tropical species. The research also allowed for the study of climatic phenomena (temperature and precipitation) recorded in tree rings in different tropical environments, suggesting that climate change may increase the sensitivity of tropical trees to climatic fluctuations.

Other works that can be mentioned are those by Fontana *et al*. (2018) who concluded that *Copaifera lucens* Dwyer growth is more dependent on precipitation than temperature, being sensitive to drought in cases of extreme water deficit during the late growing season. Campbell *et al*. (2022), when investigating the dendroclimatological potential of *Paratecoma peroba* (Record) Kuhlm. occurring in the last remnant of seasonal semi-deciduous forest in Rio de Janeiro, Brazil, found that temperature is the climatic factor with the greatest influence on the growth ring of the species. Likewise, Aragão *et al*. (2019), evaluated the dendrochronological potential of four Caatinga neotropical dry forest tree species and found that inter-annual growth variation is strongly driven by seasonal rainfall. Moreover, the authors indicated that the strong dependence of trees on precipitation is worrisome, considering that climate change scenarios forecast increased drought conditions in the Caatinga dry forest.

The relationships between climate and growth can also be modulated by non-climatic factors, including those present in microsites (Fang *et al*. 2015). Urban areas can develop a different microclimate due to the presence of numerous sources of pollutants, both vehicular and industrial, which contribute to excess heat (Kukarskih *et al*. 2022). In addition, particulate matter (PM) from these emissions can also affect the local climate and intensify heat island and thermal inversion effects, changing the way radiation is transmitted through the atmosphere (Valverde *et al*. 2020; Kukarskih *et al*. 2022; Zhang *et al*. 2022). It is worth mentioning that the retention of pollution occurs as a function of urban size, atmospheric stability, and the intensity and flow of winds (Takebayashi and Senoo 2018; Yun *et al*. 2020; Abbassi *et al*. 2022), these considered as the main mechanism that results in greater deposition of particles in trees (Chen *et al*. 2015). At the same time, the vegetation that makes up urban afforestation is subject to greater stress and can undergo changes in its structure (Rai 2016), such as morphological or anatomical parameters of the leaves (Alves *et al*. 2008; Costa *et al*. 2015), in cellular metabolic processes (Sytar 2013) in periods of cambial activity and dormancy (Iqbal *et al*. 2010a, 2010b; Vasconcellos *et al*. 2017), or even in xylem anatomy and radial increment (Leonelli *et al*. 2012; Chagas 2013; Pretzsch *et al*. 2017; Vasconcellos *et al*. 2019; Vasconcellos and Callado 2020). In this way, the task of interpreting dendroclimatic reconstructions, for example, can be aided by investigating the influences of non-climatic sources (Fang *et al*. 2015).

Different responses were observed when relating the growth of *T. catappa* with the climatic variables in the study sites. Considering that climatic data of precipitation and temperature were the same, it is suggested that factors related to atmospheric pollution may interfere with the growth of this species in an urban environment. In addition, it is possible to infer that the sensitivity of the species to the climate was lower in Resende, because the municipality is far from the urban-industrial center of Volta Redonda and, for this reason, does not receive too much influence from the pollution from this specific location.

However, when evaluating the behavior of the species as a function of the climate between the two regions of Volta Redonda (NW and SE), the trees in the northwest region showed greater sensitivity to climatic indices, for precipitation rates. Even though they are close, the trees in the southeast region did not express a significant correlation between the precipitation and temperature indices, that is, the growth of trees in this region was not dependent on the climatic factor. This fact could be explained by the possible interference of the winds throughout the year. These differences in growth between NW and SE, in addition to being explained by the influence of pollution, may also be due to the heat island effect exerted by the industrial unit through the increase in temperature in the northwest region, induced by the wind direction (Abbassi *et al*. 2022; Song *et al*. 2022).

It is noteworthy that the tree ring index presented in Fig. 3 all show a decreased trend during the 2000 to 2019 period, which may be related to the increasing climate extremes. Regoto *et al*. (2021), in an analysis of seasonal and annual trends of extreme indices of air temperature and precipitation over Brazil during the period 1961 to 2018, concluded that, in the Southern region, the climate is becoming wetter, with a reduction in consecutive dry days, especially in spring. Likewise, Córdova *et al*. (2022), in a study on the dynamics of precipitation anomalies in Tropical South America, found a significant increase in the frequency of climatic extremes occurrence (precipitation) in the south-eastern region of Brazil, which includes the 3 locations sampled in the present work. An identical situation was observed in a humid subtropical zone in the Northern Hemisphere, where climate extremes increased under global warming (Shao *et al*. 2021).

Urban Pollution Effects

The life expectancy of *Terminalia catappa* can reach 100 years, and the species can present heights that vary between 15 and 25 meters in the natural environment (Flores 2003; Thomson and Evans 2006). Although the ages of the trees in each region studied were similar, the differences that occurred between the increments of trees from Volta Redonda and trees from Resende may be associated with pollution, because the trees that grew less were those from Volta Redonda. Studies indicate that the effects of atmospheric pollution on urban trees, in general, affect photophysiological mechanisms, causing changes in the optical properties of leaves, the photosynthetic system, and in stomatal functioning (Wigley *et al*. 1984; Schweingruber 1988; Grantz *et al*. 2003; Paoletti 2009; Prajapati 2012; Mérian *et al*. 2013), consequently, interfering with the growth in height and diameter of trees (Marques *et al*. 2019; Vasconcellos *et al*. 2019; Zuidema *et al*. 2022). In addition, frequent reduction pruning, commonly practiced in urban trees that are under power lines (Carvalho Maria *et al*. 2021), can interfere not only with the canopy architecture, but also reduce the leaf coverage area, reducing the proportion of leaves and, consequently, photosynthetic rates. Therefore, the possibility of relating tree growth with air quality indices, such as the emission of particulate matter and total suspended particles, for example, may be an alternative to better understand the interference of pollution in the growth of urban trees.

The trees in the southeast region may have received less influence from urban and industrial pollution because the predominant wind direction in Volta Redonda was from southeast to northwest, according to the wind rose diagram for the region, built with the available data by INEA, between 2001 and 2018. Gioda *et al*. (2004), when evaluating the air quality in the city of Volta Redonda between some periods (the years 1995, 1996, and 1999), observed that the wind direction was east to west, so air pollutants would converge from east to west. The same authors also found that the concentration gradient of total suspended particles (TSP) was lower on the windward side of the steel industry than on the leeward side, reinforcing the hypothesis that the trees located in the northwest region would be receiving more interference from atmospheric pollution.

The sensitive behavior of trees in the northwest region as a function of precipitation may be related to the loss of leaves during the dry season. *T. catappa* trees are briefly deciduous during this season and, in some environments, can lose their leaves twice a year (Stahle 1999). The leaf surface, in turn, works as an efficient device for the deposition of pollutants, as they are highly exposed parts (Sytar 2013). In this sense, precipitation plays a significant role during the rainy season, as it helps to remove pollutants deposited on leaf surfaces, contributing to the effective growth of tree individuals. Therefore, the most expressive results of the growth indices in relation to precipitation observed during the transition from the dry season to the rainy season, may mean that the growth of *T. catappa* occurred in response to the rainy season of the previous year and that the trees present in the region considered most affected by pollution (NW) may be dependent on this climatic factor.

CONCLUSIONS

1. The dendrochronological study of the species indicated sensitivity to precipitation and temperature in an area more exposed to steel pollution by the possible interference of winds throughout the year, and it is suggested that factors related to atmospheric pollution may interfere with the growth of this species in an urban environment.
2. The species can be considered tolerant to the anthropic environment because of the longevity of the individuals analyzed under different environmental conditions.
3. The delimitation of the annual rings of the species in this research contributes to the realization of future dendrochronological studies, expanding the understanding of the behavior of this species at different regional scales.

ACKNOWLEDGMENTS

The authors are grateful to the Wood Quality Research Center (NPQM) at the Federal Rural University of Rio de Janeiro, in Brazil, and to the Laboratory of Forest Products of the University of Trás-os-Montes and Alto Douro, in Portugal. This article came from the thesis of the first author, in the Postgraduate Program in Environmental and Forestry Sciences (PPGCAF/UFRRJ). This research was funded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Finance Code 001, by National Funds by FCT, the Portuguese Foundation for Science and Technology, under the project UIDB/04033/2020 and the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) under the project NSF-FAPESP PIRE-CREATE 2017/50085-3 and 2019/27110-7.

REFERENCES CITED

Abbassi, Y., Ahmadikia, H., and Baniasadi, E. (2022). "Impact of wind speed on urban heat and pollution islands," *Urban Climate* 44, article ID 101200. DOI: 10.1016/j.uclim.2022.101200

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. D. M., and Sparovek, G. (2013). "Köppen's climate classification map for Brazil," *Meteorologische Zeitschrift* 22, 711–728. DOI: 10.1127/0941-2948/2013/0507

Alves, E. S., Tresmondi, F., and Longui, E. L. (2008). "Análise estrutural de folhas de *Eugenia uniflora* L. (Myrtaceae) coletadas em ambientes rural e urbano, SP, Brasil [Leaf anatomy of *Eugenia uniflora* L. (Myrtaceae) in urban and rural environments, São Paulo State, Brazil]," *Acta Botanica Brasilica* 22(1), 241-248. DOI: 10.1590/S0102-33062008000100023

Aragão, J. R. V., Groenendijk, P., and Lisi, C. S. (2019). "Dendrochronological potential of four neotropical dry-forest tree species: Climate-growth correlations in northeast Brazil," *Dendrochronologia* 53, 5-16. DOI: 10.1016/j.dendro.2018.10.011

Bartens, J., Grissino-Mayer, H. D., Day, S. D., and Wiseman, P. E. (2012). "Evaluating the potential for dendrochronological analysis of live oak (*Quercus virginiana* Mill.) from the urban and rural environment - An explorative study," *Dendrochronologia* 30(1), 15-21. DOI: 10.1016/j.dendro.2011.04.002

Battipaglia, G., Marzaioli, F., Lubritto, C., Altieri, S., Strumia, S., Cherubini, P., and Cotrufo, M. F. (2010). "Traffic pollution affects tree-ring width and isotopic composition of *Pinus pinea*," *Science of The Total Environment* 408(3), 586-593. DOI: 10.1016/j.scitotenv.2009.09.036

Brienen, R. J. W., Schöngart, J., and Zuidema, P. A. (2016). "Tree rings in the tropics: Insights into the ecology and climate sensitivity of tropical trees," in: *Tropical Tree Physiology*, G. Goldstein, and L. Santiago (eds), vol 6. Springer, Cham, Switzerland, pp. 439-461. DOI: 10.1007/978-3-319-27422-5_20

Brienen, R. J., W., and Zuidema, P. A. (2005). "Relating tree growth to rainfall in Bolivian rain forests: A test for six species using tree ring analysis," *Oecologia* 146, 1-12. DOI: 10.1007/s00442-005-0160-y

Buras, A. (2017). "A comment on the expressed population signal," *Dendrochronologia* 44, 130-132. DOI: 10.1016/j.dendro.2017.03.005

Campbell, G., Callado, C. H., Costa, W. S, Marques, J. D. B. C., Pireda, S., and Cunha, M. (2022). "Growth ring response in *Paratecoma peroba* (Record) Kuhlm. of seasonal semideciduous forest in Southeast Brazil," *Dendrochronologia* 72, article ID 125924. DOI: 10.1016/j.dendro.2022.125924

Carvalho Maria, T. R. B., Biondi, D., Behling, A., and Sousa, N. J. (2021). "Evaluation of *Terminalia catappa* street trees: A case study in Itanhaém – São Paulo, Brazil," *Urban Forestry and Urban Greening* 66, article ID 127373. DOI: 10.1016/j.ufug.2021.12737

Chagas, M. P. (2013). *Anéis de Crescimento do Lenho de Árvores como Monitores Ambientais: Avaliação Temporal e Espacial da Poluição Atmosférica na Cidade de Paulínia, São Paulo [Tree Wood Growth Rings as Environmental Monitors: Temporal and Spatial Assessment of Atmospheric Pollution in the City of Paulínia, São Paulo]*, Doctoral Thesis, University of São Paulo, Luiz de Queiroz School of Agriculture, Piracicaba, São Paulo, SP, Brazil.

Chagas, M. P. (2009). *Caracterização dos Anéis de Crescimento e Dendrocronologia de Árvores de Grevillea robusta A. Cunn, Hovenia dulcis Thunb., Persea americana Mill., Tabebuia pentaphylla Hemsl. e Terminalia catappa L. nos Municípios de Piracicaba e Paulínia, SP [Characterization of Growth Rings and Dendrochronology of Trees of Grevillea robusta A. Cunn, Hovenia dulcis Thunb., Persea americana Mill., Tabebuia pentaphylla Hemsl. and Terminalia catappa L. in the Municipalities of Piracicaba and Paulínia, SP]*, Master's Thesis, University of São Paulo, Luiz de Queiroz School of Agriculture, Piracicaba, São Paulo, SP, Brazil.

Chen, J., Yu, X., Sun, F., Lun, X., Fu, Y., Jia, G., Zhang, Z., Liu, X., Mo, L., and Bi, H. (2015). "The concentrations and reduction of airborne particulate matter (PM10, PM2.5, PM1) at shelterbelt site in Beijing," *Atmosphere (Basel)* 6(5), 650–676. DOI: 10.3390/atmos6050650

Cook, E. R., and Holmes, R. L. (1996). "Guide for computer program ARSTAN," in: *The International Tree-ring Data Bank Program Library Version 2.0 User's Manual*, Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ, USA, pp. 75-87.

Cook, E., Briffa, K., Shiyatov, S., Mazepa, V., and Jones, P. D. (1990). "Data analysis," in: *Methods of Dendrochronology*, Springer, Dordrecht, Netherlands, pp. 97-162. DOI: 10.1007/978-94-015-7879-0_3

Córdova, M., Célleri, R., and Delden, A. (2022). "Dynamics of precipitation anomalies in tropical South America," *Atmosphere (Basel)* 13(6), article 972. DOI: 10.3390/atmos13060972

Costa, V. B. S., Silva, W. J. M. S., Almeida, G. M. A., Ferreira, M. H. G., Oliveira, T. H., Galvíncio, J. D., and Pimentel, R. M. M. (2015). "Influence of air pollution in *Terminalia catappa* L. in urban areas," *Revista Brasileira de Geografia Física* 8, 236-252. DOI: 10.26848/rbgf.v8i2.233607

Fang, K., Chen, D., Gou, X., D'Arrigo, R., and Davi, N. (2015). "Influence of non-climatic factors on the relationships between tree growth and climate over the Chinese Loess Plateau," *Global and Planetary Change* 132, 54-63. DOI: 10.1016/j.gloplacha.2015.06.008

Flores, E. M. (2003). "*Terminalia catappa* L.: Tropical tree seed manual," Species Descriptions, (https://rngr.net/publications/ttsm/species/PDF.2004-03-16.0017), Accessed 6 Aug 2022.

Fontana, C., Pérez-De-Lis, G., Santini-Junior, L., Botosso, P. C., Nabais, C., Tomazello-Filho, M., and Lousada, J. L. P. C. (2018a). "Wood anatomy and growth ring boundaries of *Copaifera lucens* (Fabaceae)," *IAWA Journal* 39, 395-405. DOI: 10.1163/22941932-20170209

Fontana, C., Reis-Avila, G., Nabais, C., Botosso, P. C., and Oliveira, J. M. (2018b). "Dendrochronology and climate in the Brazilian Atlantic Forest: Which species, where and how," *Neotropical Biology and Conservation* 13(4), 321-333. DOI: 10.4013/nbc.2018.134.06

Fritts, H. (1976). *Tree Rings and Climate*, Academic Press, Cambridge, MA, USA. DOI: 10.1016/B978-0-12-268450-0.X5001-0Gaspard, D. T., Venegas-González, A., Beeckman, H., Randriamalala, J. R., Tomazello-Filho, M., Ridder, M., and Ramananantoandro, T. (2018). "Tree ring responses to climate variability of xerophytic thickets from South Soalara, Madagascar," *Dendrochronologia* 49, 57-67. DOI: 10.1016/j.dendro.2018.02.003

Geraldo, S. M., Canteras, F. B., and Moreira, S. (2014). "Biomonitoring of environmental pollution using growth tree rings of *Tipuana tipu*: Quantification by synchrotron radiation total reflection X-ray fluorescence," *Radiation Physics and Chemistry* 95, 346-348. DOI: 10.1016/j.radphyschem.2013.03.012

Gillner, S., Bräuning, A., and Roloff, A. (2014). "Dendrochronological analysis of urban trees: Climatic response and impact of drought on frequently used tree species," *Trees - Structure and Function* 28, 1079-1093. DOI: 10.1007/s00468-014-1019-9

Gioda, A., Sales, J. A., Cavalcanti, P. M. S., Maia, M. F., Maia, L. F. P. G., and Aquino Neto, F. R. (2004). "Evaluation of air quality in Volta Redonda, the main metallurgical industrial city in Brazil," *Journal of the Brazilian Chemical Society* 15(6), 856-864. DOI: 10.1590/S0103-50532004000600012

Grantz, D. A., Garner, J. H. B., and Johnson, D. W. (2003). "Ecological effects of particulate matter," *Environment International* 29(2-3), 213-239. DOI: 10.1016/S0160-4120(02)00181-2

Grissino-Mayer, H. D. (2001). *Evaluating Crossdating Accuracy: A Manual and Tutorial for the Computer Program COFECHA*, Tree -Ring Research, Department of Geography, The University of Tennessee, Knoxville, TN, USA.

Holmes, R. L., Adams, R. K., and Fritts, H. C. (1986). *Tree-Ring Chronologies of Western North America : California Eastern Oregon and Northern Great Basin with Procedures Used in the Chronology Development Work Including Users Manuals for Computer Programs Cofecha and Arstan*, Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ, USA.

Iqbal, M., Jura-Morawiec, J., and WŁoch, W. (2010a). "Foliar characteristics, cambial activity, and wood formation in *Azadirachta indica* A. Juss. as affected by coal–smoke pollution," *Flora: Morphology, Distribution, Functional Ecology of Plants* 205(1), 61-71. DOI: 10.1016/j.flora.2008.12.003

Iqbal, M., Mahmooduzzafar, Aref, I. M., and Khan, P. R. (2010b). "Behavioral responses of leaves and vascular cambium of *Prosopis cineraria* (L.) Druce to different regimes of coal-smoke pollution," *Journal of Plant Interactions* 5(2), 117-133. DOI: 10.1080/17429140903438084

Isinkaralar, K. (2022). "The large-scale period of atmospheric trace metal deposition to urban landscape trees as a biomonitor," *Biomass Conversion and Biorefinery* Online, 1-10. DOI: 10.1007/s13399-022-02796-4

Kukarskih, V. V., Devi, N. M., Bubnov, M. O., Komarova, A. V., and Agafonov, L. I. (2022). "Radial growth of Scots pine in urban and rural populations of Ekaterinburg megalopolis," *Dendrochronologia* 74, article ID 125974. DOI: 10.1016/j.dendro.2022.125974

Leonelli, G., Battipaglia, G., Siegwolf, R. T. W., Saurer, M., Morra di Cella, U., Cherubini, P., and Pelfini, M. (2012). "Climatic isotope signals in tree rings masked by air pollution: A case study conducted along the Mont Blanc Tunnel access road (Western Alps, Italy)," *Atmospheric Environment* 61, 169-179. DOI: 10.1016/j.atmosenv.2012.07.023

Locosselli, G. M., Camargo, E. P., Moreira, T. C. L., Todesco, E., Andrade, M. F., André, C. D. S., André, P. A., Singer, J. M., Ferreira, L. S., Saldiva, P. H. N., *et al.* (2019). "The role of air pollution and climate on the growth of urban trees," *Science of The Total Environment* 666, 652-661. DOI: 10.1016/j.scitotenv.2019.02.291

López, L., and Villalba, R. (2020). "Climate-growth relationships for *Aspidosperma tomentosum* Mart. in South American tropical dry forests," *Annals of Forest Science* 77, article 96. DOI: 10.1007/s13595-020-01001-8

Marcelo-Peña, J. L., Roig, F. A., Goodwin, Z. A., and Tomazello-Filho, M. (2020). "Characterizing growth rings in the trees of Perú: A wood anatomical overview for potential applications in dendroecological-related fields," *Dendrochronologia* 62, article ID 125728. DOI: 10.1016/j.dendro.2020.125728

Marques, D. M., Silva, A. B., Mantovani, J. R., Magalhães, P. C., and Souza, T. C. (2019). "Root morphology and leaf gas exchange in *Peltophorum dubium* (Spreng.) Taub. (Caesalpinioideae) exposed to copper-induced toxicity," *South African Journal of Botany* 121, 186-192. DOI: 10.1016/j.sajb.2018.11.007

Mérian, P., Pierrat, J., and Lebourgeois, F. (2013). "Effect of sampling effort on the regional chronology statistics and climate–growth relationships estimation," *Dendrochronologia* 31, 58-67. DOI: 10.1016/j.dendro.2012.07.001

Montine, P. S. M., Viana, N. F., Almeida, F. S., Dáttilo, W., Santanna, A. S., Martins, L., and Vargas, A. B. (2014). "Seasonality of epigaeic ant communities in a Brazilian Atlantic rainforest," *Sociobiology* 61(2), 178-183. DOI: 10.13102/sociobiology.v61i2.178-183

Paoletti, E. (2009). "Ozone and urban forests in Italy," *Environmental Pollution* 157(5), 1506-1512. DOI: 10.1016/j.envpol.2008.09.019

Peiter, P., and Tobar, C. (1998). "Poluição do ar e condições de vida: Uma análise geográfica de riscos à saúde em Volta Redonda, Rio de Janeiro, Brasil [Air pollution and living conditions: A geographical analysis of health risk in Volta Redonda, Rio de Janeiro, Brazil]," *Caderno de Saúde Pública* 14, 473-485. DOI: 10.1590/s0102-311x1998000300003

Prajapati, S. K. (2012). "Ecological effect of airborne particulate matter on plants," *Environmental Skeptics and Critics* 1, 12-22.

Pretzsch, H., Biber, P., Uhl, E., Dahlhausen, J., Schütze, G., Perkins, D., Rötzer, T., Caldentey, J., Koike, T., van Com, T., *et al.* (2017). "Climate change accelerates growth of urban trees in metropolises worldwide," *Scientific Reports* 7, article 15403. DOI: 10.1038/s41598-017-14831-w

Rai, P. K. (2016). "Impacts of particulate matter pollution on plants: Implications for environmental biomonitoring," *Ecotoxicology and Environmental Safety* 129, 120-136. DOI: 10.1016/j.ecoenv.2016.03.012

Regoto, P., Dereczynski, C., Chou, S., and Bazzanela, A. (2021). "Observed changes in air temperature and precipitation extremes over Brazil," *International Journal of Climatology* 41, 5125-5142. DOI: 10.1002/joc.7119

Ribeiro, R. T. M., Marquet, N., and Loiola, M. I. B. (2020). "Combretaceae in Flora do Brasil 2020 [Combretaceae in the flora of Brazil 2020]," Jardim Botânico do Rio Janeiro, (https://floradobrasil2020.jbrj.gov.br/reflora/floradobrasil/FB6913), Accessed 17 June 2022.

Ridder, M., Trouet, V., van den Bulcke, J., Hubau, W., van Acker, J., and Beeckman, H. (2013). "A tree-ring based comparison of *Terminalia superba* climate-growth relationships in West and Central Africa," *Trees - Structure and Function* 27, 1225-1238. DOI: 10.1007/s00468-013-0871-3

Rocha, N. L. T., and Guimarães, C. S. (2017). "Estudo da Qualidade do Ar e a Atividade Siderúrgica na Cidade de Volta Redonda [Study of air quality and steel activity in the city of Volta Redonda]," *Cadernos UniFOA* 12, 25–36.

Ruwanpathirana, N. D. (2014). “Use of wood characteristics in identification of selected *Terminalia* species growing in Sri Lanka,” *Journal of Tropical Forestry and Environment* 4(2), 64-72.
Schweingruber, F. H. (1988). *Tree Rings: Basics and Applications of Dendrochronology*, Springer, Dordrecht, Netherlands. DOI: 10.1007/978-94-009-1273-1
Sensuła, B., Wilczyński, S., Monin, L., Allan, M., Pazdur, A., and Fagel, N. (2017). “Variations of tree ring width and chemical composition of wood of pine growing in the area nearby chemical factories,” *Geochronometria* 44, 226-239. DOI: 10.1515/geochr-2015-0064
Shao, H., Zhang, Y., Gu, F., Shi, C., Miao, N., and Liu, S. (2021). “Impacts of climate extremes on ecosystem metrics in southwest China,” *Science of The Total Environment* 776, article ID 145979. DOI: 10.1016/j.scitotenv.2021.145979
Singh, M. K., Sharma, M. B., and Sharma, C. L. (2013). “Wood anatomical variations in some *Terminalia* species of Assam,” *International Journal of Botany and Research* 3(2), 13-18.
Song, D., Zhang, X., Zhou, X., Shi, X., and Jin, X. (2022). "Influences of wind direction on the cooling effects of mountain vegetation in urban area,” *Building and Environment* 209 (1), article 108663. DOI: 10.1016/j.buildenv.2021.108663
Speer, J. H. (2010). *Fundamentals of Tree-ring Research*, The University of Arizona Press, Tucson, AZ, USA.
Stahle, D. W., Mushove, P. T., Cleaveland, M. K., Roig, F., and Haynes, G. A. (1999). “Management implications of annual growth rings in *Pterocarpus angolensis* from Zimbabwe,” *Forest Ecology and Management* 124(2-3), 217-229. DOI: 106.101/S0378-1127(99)00075-4
Sytar, O., Kumar, A., Latowski, D., Kuczynska, P., Strzałka, K., and Prasad, M. N. V. (2013). “Heavy metal-induced oxidative damage, defense reactions, and detoxification mechanisms in plants,” *Acta Physiologiae Plantarum* 35, 985-999. DOI: 10.1007/s11738-012-1169-6
Takebayashi, H., and Senoo, M. (2018). “Analysis of the relationship between urban size and heat island intensity using WRF model,” *Urban Climate* 24, 287-298. DOI: 10.1016/j.uclim.2016.12.003
Thomson, L. A. J., and Evans, B. (2006). “*Terminalia catappa* (tropical almond),” *Species Profiles for Pacific Island Agroforestry* 2, 1-20.
Tomazello Filho, M., Botosso, P. C., and Lisi, C. S. (2001). “Análise e aplicação dos anéis de crescimento das árvores como indicadores ambientais: Dendrocronologia e dendroclimatologia [Analysis and application of tree growth rings as environmental indicators: Dendrochronology and dendroclimatology],” in: *Indicadores Ambientais: Conceitos e Aplicações*, Educ, São Paulo, SP, Brazil, pp. 145-171.
Trouet, V., Esper, J., and Beeckman, H. (2010). “Climate/growth relationships of *Brachystegia spiciformis* from the miombo woodland in south central Africa,” *Dendrochronologia* 28, 161-171. DOI: 10.1016/j.dendro.2009.10.002
Urbinati, C. V., Azevedo, A. A., da Silva, E. A. M., and Lisboa, P. L. B. (2003). “Wood structural quantitative variation of the *Terminalia ivorensis* A. Chev., Combretaceae,” *Acta Botanica Brasilica* 17(3), 421-437. DOI: 10.1590/S0102-33062003000300009
Vaganov, E. A., Anchukaitis, K. J., and Evans, M. N. (2011). “How well understood are the processes that create dendroclimatic records? A mechanistic model of the climatic control on conifer tree-ring growth dynamics,” in: *Dendroclimatology. Developments*

in Paleoenvironmental Research, M. Hughes, T. Swetnam, H. Diaz (eds.), vol. 11, Springer, Dordrecht, Netherlands, pp. 37-75. DOI: 10.1007/978-1-4020-5725-0_3

Valverde, M. C., Coelho, L. H., Cardoso, A. O., Junior, H. P., Brambila, R., Boian, C., Martinelli, P. C., and Valdambrini, N. M. (2020). "Urban climate assessment in the ABC Paulista Region of São Paulo, Brazil," *Science of The Total Environment* 735, article ID 139303. DOI: 10.1016/j.scitotenv.2020.139303

Van Vliet, G. J. C. M. (1979). "Wood anatomy of the Combretaceae," *Blumea* 25(1), 141-223.

Vasconcellos, T. J., and Callado, C. H. (2020). "Wood anatomy of *Ceiba speciosa* (A. St.-Hil.) Ravenna under urban pollution," *IAWA Journal* 41, 30-47. DOI: 10.1163/22941932-00002109

Vasconcellos, T. J., Tomazello-Filho, M., and Callado, C. H. (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. DOI: 10.1016/j.dendro.2018.12.004

Vasconcellos, T. J., Cunha, M., and Callado, C. H. (2017). "A comparative study of cambium histology of *Ceiba speciosa* (A. St.-Hil.) Ravenna (Malvaceae) under urban pollution," *Environmental Science and Pollution Research International* 24, 12049-12062. DOI: 10.1007/s11356-015-6012-3

Volná, V., Blažek, Z., and Krejčí, B. (2021). "Assessment of air pollution by PM10 suspended particles in the urban agglomeration of Central Europe in the period from 2001 to 2018," *Urban Climate* 39, article ID 100959. DOI: 10.1016/j.uclim.2021.100959

Wang, K., Tian, H., Hua, S., Zhu, C., Gao, J., Xue, Y., Hao, J., Wang, Y., and Zhou, J. (2016). "A comprehensive emission inventory of multiple air pollutants from iron and steel industry in China: Temporal trends and spatial variation characteristics," *Science of the Total Environment* 559, 7-14. DOI: 10.1016/j.scitotenv.2016.03.125

Wigley, T. M. L., Briffa, K. R., and Jones, P. D. (1984). "On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology," *Journal of Applied Mathematics and Computing* 23(2), 201-213. DOI: 10.1175/1520-0450(1984)023<0201:OTAVOC>2.0.CO;2

Yun, G. Y., Ngarambe, J., Duhirwe, P. N., Ulpiani, G., Paolini, R., Haddad, S., Vasilakopoulou, K., and Santamouris, M. (2020). "Predicting the magnitude and the characteristics of the urban heat island in coastal cities in the proximity of desert landforms. The case of Sydney," *Science of The Total Environment* 709, article ID 136068. DOI: 10.1016/j.scitotenv.2019.136068

Zar, J. H. (2010). *Biostatistical Analysis*, Prentice Hall, Hoboken, NJ, USA.

Zhang, G., Ren, Y., Yu, Y., and Zhang, L. (2022). "The impact of air pollution on individual subjective well-being: Evidence from China," *Journal of Cleaner Production* 336, article ID 130413. DOI: 10.1016/j.jclepro.2022.130413

Zuidema, P. A., Babst, F., Groenendijk, P., Trouet, V., Abiyu, A., Acuna-Soto, R., Adenesky-Filho, E., Alfaro-Sanchez, R., Aragao, J. R. V., Assis-Pereira, G., *et al.* (2022). "Tropical tree growth driven by dry-season climate variability," *Nature Geoscience* 15, 269-276. DOI: 10.1038/s41561-022-00911-8

Article submitted: March 29, 2023; Peer review completed: April 29, 2023; Revised version received and accepted: May 9, 2023; Published: May 22, 2023.
DOI: 10.15376/biores.18.3.4771-4789