



# Integrating species and successional classes for wood production in a mixed forest restoration system in a neotropical region

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**Abstract** As forests in neotropical regions, particularly in developing countries, are devastated, interventions to restore biodiversity and its ecological functions are needed. Rural producers have thus been encouraged to grow trees for wood production as an economic activity. The objective of this study was to quantify the increment of wood density of four forest species from different successional classes of a mixed system of restoration in a neotropical forest in Brazil. Tree discs were sampled at breast height and analyzed radially by X-ray densitometry to obtain apparent density and basic density. Three trees each of a species from the pioneer, early and late secondary successional stages and of the dominant species in the climax community. The radial profiles indicated increasing density from the pith to bark of trunks, except for some variations due to wood defects and growth. Average

density was 0.576 g cm<sup>-3</sup>, 0.655 g cm<sup>-3</sup>, 0.706 g cm<sup>-3</sup> and 0.775 g cm<sup>-3</sup>, respectively, for *Peltophorum dubium*, *Schinus terebinthifolius*, *Cariniana estrellensis* and *Hymenaea courbaril*. Radial profiles indicated higher amplitudes in the apparent densities for slow-growing species. X-ray densitometry generated parameters such as minimum, average and maximum densities, and radial density variations. These parameters are important for understanding the ecological functional role of successional classes of the Atlantic Forest from the Neotropical region.

**Keywords** X-ray densitometry · Timber species of neotropical forest · Successional classes of forest species · Maintenance of forest restoration

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## Introduction

To restore the biodiversity and ecological functions of devastated forests and large degraded areas in tropical regions, especially in developing countries, interventions are urgently needed (Rodrigues et al. 2009; Slik et al. 2015). The need is even more urgent for neotropical forests that support most of the tree species on the planet (Slik et al. 2015; Beech et al. 2017; Amazonas et al. 2018). In biomes where ecological functioning has been compromised and much of the native biodiversity is now seriously threatened, ecological restoration is needed on a large scale, mainly to restore the ecological services it provides (Engel and Parrota 2001; Paula et al. 2004; Rodrigues et al. 2011; Sos Mata Atlântica 2015). These are minimum actions necessary for the recovery and permanent preservation of legally protected reserves that are primarily rural areas. Including species with wood potential in restoration processes through mixed plantations and allowing silvicultural management are important for valuation for

commercial purposes and for socioeconomic and socioenvironmental aspects (Gandolfi et al. 1995; Amazonas et al. 2018). This process enables the perpetuation of native neotropical wood species dominated by traditional silviculture based on *Eucalyptus* and *Pinus* (Kelty 2006; Amazonas et al. 2018) and supports the producer as the landscape is recomposed in his/her rural area, producing wood to generate financial resources and maintain the plantations (Amazonas et al. 2018; Brancalion et al. 2012; Lamb 2005).

Commercial mixed plantations generally comprise two to four species and are often preferred because they can produce a larger quantity or higher quality of wood (or biomass) than monocultures can (Kelty 2006). The demand for wood products coincides with a growing international demand for forest and landscape restoration and for forests that can be used to achieve multiple objectives (FAO 2016; Brancalion and Chazdon 2017; Chazdon et al. 2017). The properties of wood enable its use for multiple products and purposes. However, we need to understand the interaction between different successional ecological classes and their effect on wood properties. Wood density, in particular, is an efficient, widely studied and used genetic variable for characterizing the quality of wood to determine its best use (Ferreira and Tomazello Filho 2009; Lobão et al. 2010). Although several factors influence wood density, it can be considered as a universal index for evaluating the wood due to the ease of determination and the excellent relation to wood use (Tomazello Filho et al. 2005; Santos and Sansígolo 2007; Sette Júnior et al. 2009). This property is complex, resulting from the combination of anatomical, physical and chemical characters and can vary significantly with age, source, place of origin, spacing, growth rate, between genera and species, and even between trees of the same species (Souza et al. 1986; Sette Júnior et al. 2009).

Wood density is primary property that limits the ultimate use of a wood product. In some cases, when shorter cutting cycles for power generation, firewood and posts, high densities are increasingly required. Knowledge of forest species with potential for use in forest restoration systems that can simultaneously contribute to the ecological and economic success of an ecosystem and provide wood for suitable use, has been the constant goal for mixed planting systems to restore and maintain the system by cutting some species in a shorter period of time. Toward this goal, we thus analyzed here the increase in wood density of four forest species from different successional classes from a mixed forest restoration system from the neotropical region.

## Material and methods

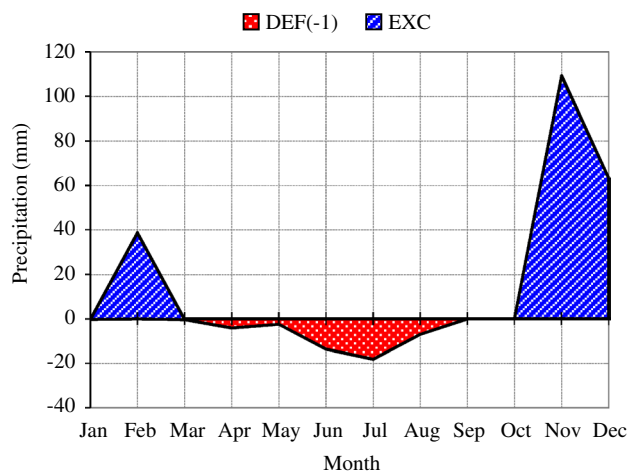
### Experimental area

Trees of 20 pioneer and non-pioneer native species constitute an experimental plantation established in 2004 in plots (12 rows  $\times$  11 plants = 132 plants), with 3 m  $\times$  2 m spacing, in a legal reserve area of the Experimental Station of Forestry Sciences of Anhembi, São Paulo State, Brazil. This forest plantation integrates the project “Models of restoration of degraded areas of the Atlantic Forest aiming at carbon sequestration”. The plantation area is located at 22° 40' S latitude and 48° 10' W longitude, at 455 m a.s.l., in sandy, deep soil (Stape et al. 2006).

The climate of the region is classified as mesothermal Cwa (Köppen), with hot, rainy summers and moderately cold, dry winters. The average annual temperature is 23.0 °C, annual average rainfall is 1100 mm, with 20 mm of annual water deficit in the dry months (April to September). During 2014–2015, an extreme climatic event was recorded, with a reduction in rainfall, and the water balance was calculated using the method of Thornthwaite and Mather (1955) to be 300 mm for available soil water capacity for the type of soil in the experimental area (Fig. 1).

### Experimental methods

One species from each succession groups was selected (*Schinus terebinthifolius*, *Peltophorum dubium*, *Cariniana estrellensis* and *Hymenaea courbaril*, Table 1), and in September of 2015, three trees of each species were felled. We then removed discs from the wood (10 cm thick) at breast height (DBH, 1.30 m from the ground level),



**Fig. 1** Monthly water balance from January 2014 to December 2015. DEF (– 1) is water deficit; EXC is water surplus

**Table 1** Forest species, family and succession groups

Species	Common name in Brazil	Family	Group succession <sup>a</sup>
<i>Schinus terebinthifolius</i>	Aroeira pimenteira	Anacardiaceae	Pioneer
<i>Peltophorum dubium</i>	Canafístula	Fabaceae (caesalpinoideae)	Early secondary
<i>Cariniana estrellensis</i>	Jequitibá-Branco	Lecythidaceae	Late secondary
<i>Hymenaea courbaril</i>	Jatobá	Fabaceae (caesalpinoideae)	Climax

<sup>a</sup>Ferreti et al. 1955**Table 2** Dendrometric information of felled trees

Species	DBH, width diameter (cm)	DBH, average class (cm)	Total height (m)
<i>Schinus terebinthifolius</i>	5.10	8.30	3.90
<i>Peltophorum dubium</i>	5.20	10.20	4.10
<i>Cariniana estrellensis</i>	2.80	7.80	1.60
<i>Hymenaea courbaril</i>	4.10	9.10	2.90

DBH: diameter at 1.30 m above ground

These species had previously been inventoried, so that the individuals selected and sampled for this study were the ones that most approached the average classes of each species of the dendrometric data presented in Table 2.

### Basic and apparent wood density of the four tree species

Radial test specimens (2 × 1 cm, width and height) were cut from wood samples of the trunk of the four species and conditioned in an acclimatization chamber (20 °C, 50% RH and 12% final moisture) for the determination of the basic density and apparent density (ABNT 1997, 2003) (Eqs. 1 and 2). By comparing both parameters, we can identify the differences and characterize the species, observing the variations of the same material submitted to different moisture contents.

$$B_d = \frac{a_m}{v_{\text{sat}}} \quad (1)$$

$$A_d = \frac{m_{12\%}}{v_{12\%}} \quad (2)$$

where  $B_d$  is basic density ( $\text{g cm}^{-3}$ );  $a_m$  is anhydrous mass (g);  $v_{\text{sat}}$  is saturated volume ( $\text{cm}^3$ );  $A_d$  is apparent density ( $\text{g cm}^{-3}$ );  $m_{12\%}$  and  $v_{12\%}$  are mass and volume of the wood measured at 12% moisture.

The radial microdensity profile of the wood (X-ray densitometry) consisted of scanning the radial cross-section

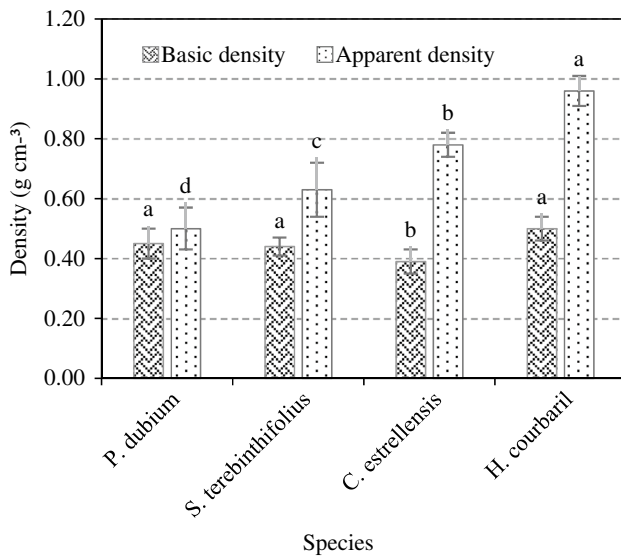
through collimated X-ray beam (80  $\mu\text{m}$ , distance between points) in a QTRS-01X device (Quintek Measurement Systems), which allowed obtaining the value of the average, maximum and minimum densities of the growth rings (QMS 1999; Tomazello Filho et al. 2008; Castro et al. 2014). In the determination of the trees of the species with largest wood/volume, the normality, homoscedasticity and analysis of variance tests were applied, with the Tukey test (95% probability) to compare the averages. All analyses were processed in R software (R Core Team 2014).

## Results and discussion

### Basic wood density of the trees

*C. estrellensis*, a species classified as late secondary, had the lowest basic density of wood. The other species, from the other successional groups studied, had values between  $0.44 \text{ g cm}^{-3}$  (*S. terebinthifolius*) and  $0.500 \text{ g cm}^{-3}$  (*H. courbaril*) (Fig. 2). Late secondary species, compared to climax species, have the fastest growth, which favors an increase in wood and reduces the basic density (Swaine and Whitmore 1988). Reduced availability of edaphoclimatic resources for plants as a result of interactions among different species and their respective classes interferes in wood development (Piotto 2008). Ecophysiological characteristics, such as growth velocity and shade tolerance, used to distinguish successional groups are also important determinants for an increase in density (Chazdon 2008).

The highest basic density was detected in the wood of *H. courbaril*, a climax species, characteristic of mature forest. This species, the last to be established within an ecological system, has slow growth, which promotes maturation and lignification of cell walls, and as a result, increase in wood density. In spite of this, the species classified as early did not differ statistically from *H. courbaril*, indicating that the species factor is strong and should be considered in the density analysis because it is a property with high genetic heritability. The four species investigated had densities considered medium, making them suitable for the wood uses within a rural property.



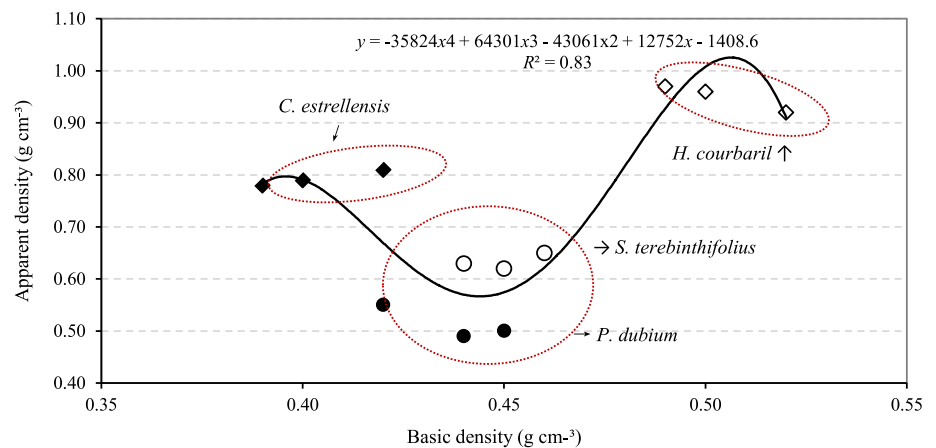
**Fig. 2** Basic and apparent density of the wood of the trees of different successional stages. Equal letters do not differ between species for each variable analyzed by the Tukey test at 95% probability level. *S.*, *Schinus*; *P.*, *peltophorum*; *C.*, *Cariniana*; *H.*, *Hymenaea*

### Apparent wood density of the trees

Species with fast growth (pioneers) had a greater increase in density than in the very slow-growing climax species (Fig. 2).

In summary, species in order of lowest to highest apparent densities were (1) *P. dubium* ( $0.50 \text{ g cm}^{-3}$ ), classified as fast-growing early secondary species; (2) *S. terebinthifolius* ( $0.63 \text{ g cm}^{-3}$ ), classified as a very fast-growing pioneer species, with a high light requirement for its establishment; (3) *C. estrellensis*: ( $0.78 \text{ g cm}^{-3}$ ), classified as slow-growing late secondary species, which requires varying amounts of light as a function of planting arrangement; and, (4) *H. courbaril*: ( $0.98 \text{ g cm}^{-3}$ ), classified as a slow-growing, climax species, with a strong light requirement as an adult.

**Fig. 3** Relationship between the basic and apparent wood density of trees of different successional stages



The species of slower growth had greater increments of density (*C. estrellensis* and *H. courbaril*). When considering a mixed forest system for ecological restoration, it is important to integrate fast-growing species that form and recompose the landscape with slower-growing species to enable the removal of wood with higher basic density after a certain time. The benefits of such population dynamics involve both restoration and economic return, where the use of higher-density species enables wood use for live fences, support posts, firewood, among others. However, ecological, silvicultural and phytosociological aspects should be observed previously for large-scale implementation. Apparent density depends on the climatic conditions under which it was determined because it considers the moisture content of the material, but it is a variable that is strongly related to the basic density (Rezende et al. 1988; Padilha and Marco Júnior 2018), a genetic variable considered as the main attribute for wood use. In general, apparent density values are higher than those of basic density as they include the volume of wood voids (pores). In this study, this relation was described by a fourth-order asymptotic curve (Fig. 3).

Table 3 shows a considerable variation in the basic wood density of the species studied, as a function of variation in age and planting arrangement. We observed a tendency corresponding to that found in the relation of the basic and apparent wood density of the trees (Fig. 3), in which the climax species has a higher wood density, followed in decreasing order by the late secondary, early secondary and pioneer species.

### Radial profile of microdensity and apparent density of wood

The faster growing species *S. terebinthifolius* (pioneer) and *P. dubium* (early secondary) had closer values for apparent densities, while values for slower growing species had wider ranges and higher values. The grouped species, pioneer and

**Table 3** Basic density and apparent density of the forest species of the different successional stages

Species	Age (years)	Density ( $\text{g cm}^{-3}$ )		Reference
		Basic	Apparent (12%–15%)	
<i>Schinus terebinthifolius</i>	12	0.49	-	Nogueira Junior (2010)
<i>Peltophorum dubium</i>	14	0.50	0.70	Xavier (2016)
	28	0.46	-	Lima et al. (2015)
	10	0.50	0.64	Vivian et al. (2010)
	-	0.56	-	Moreira (1999)
<i>Cariniana estrellensis</i>	-	0.60–0.69	0.70–0.78	Jankowsky et al. (1990)
	-	0.46	-	Fearnside (1997a, b)
	-	0.53	-	Nogueira Junior (2010)
<i>Hymenaea courbaril</i>	12	0.53	-	Nogueira Junior (2010)
	-	-	0.80–1.10	Albuquerque et al. (2016)
	-	0.74	-	Fearnside (1997a, b)

early secondary, had typical pith, with lower apparent density (Fig. 4), as verified in the radial profiles.

We detected an increase in the apparent density in the pith to bark direction in fast-growing species. Radial profiles of apparent density of the wood are consistent with the values reported in the literature and characterized by lower density near the pith, increasing toward the bark (Amaral and Tomazello Filho 1998; Tomazello Filho et al. 2008; Sette et al. 2009). In *H. courbaril*, there was a trend of higher density values near the pith, which is associated with the presence of nodes. The qualitative analysis showed that the wood of this species has a less variation in density in the profile, highlighted by the similarity in gray tones (lighter gray corresponds to higher density, darker gray to lower density), although the total radial density is higher (Fig. 4). Albuquerque et al. (2016) described *H. courbaril* as having good dendrochronological potential due to the abrupt decrease in density at the ring boundary because of the parenchyma, but in the mixed planting used here, the microdensity profile showed greater homogeneity.

Regions of the density profile characterized by higher values of apparent density are related to the formation of fibrous zones in the wood, where there is a predominance of thick wall fibers, smaller diameter of the lumen, and vessels of smaller diameter and frequency, typical of latewood (Ferreira and Tomazello Filho 2009). The formation of growth bands of higher and lower density wood is probably a result of the seasonality of the trunk activity of the trees, due to climatic variations, mainly related to the seasons with higher and lower availability of water, temperature and photoperiod. The greater alternation of values throughout the section, regardless of the studied species, is possibly due to seasonal variations, typical of neotropical regions. The effect of climate variations on annual growth rings could be evaluated using X-ray densitometry. According to Tomazello Filho et al. (2001), trees show a reaction to environmental variables that affect their numerous physiological processes,

such as respiration, sap flow, transpiration, rate of cell division among other factors, affecting cambial activity and wood anatomy.

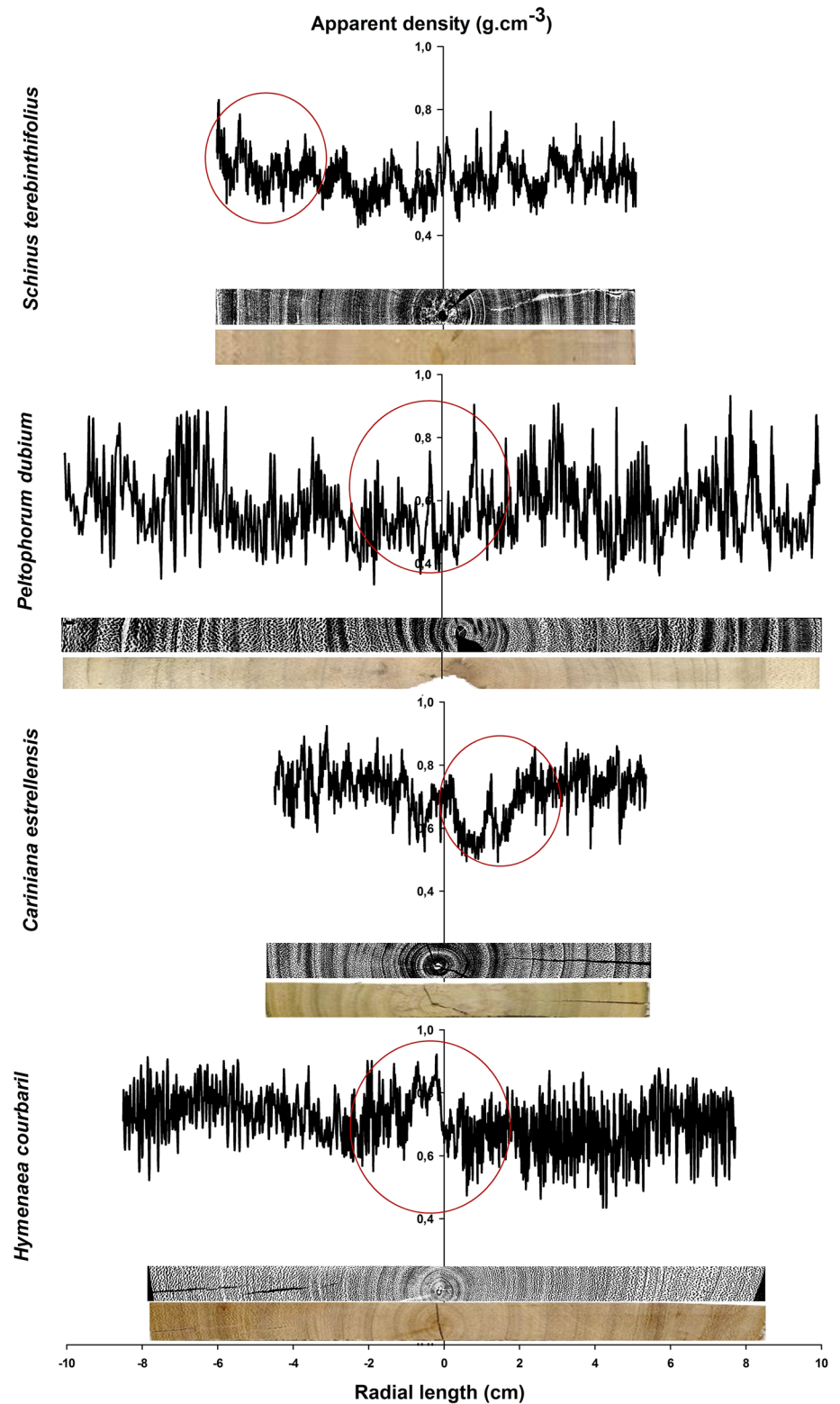
The mean apparent wood density of the four forest species with potential for ecological restoration and economic maintenance differed significantly, making it possible to group them using Tukey's test ( $p < 0.05$ ) into three classes: (1) lower density, *P. dubium*; (2) intermediate density, *S. terebinthifolius*; and (3) higher density, *C. estrellensis* and *H. courbaril* (Table 3). Trees with the highest apparent density usually have a higher percentage of latewood, mainly in adult wood, resulting in an increase in their mean apparent density due to the greater attenuation of X-rays. The trees with the lowest apparent density of the wood have higher percentage of early wood in the juvenile wood, reducing the average value of the apparent density (Castro et al. 2014).

The minimum wood density and maximum wood density of the four species studied ranged from 0.34 (*P. dubium*) to 0.99  $\text{g cm}^{-3}$  (*H. courbaril*). However, the highest amplitudes were observed for slow-growing species. The density of the wood encompasses different components of the xylem; therefore, many variables can influence the density values (Roque and Tomazello Filho 2007). The maximum apparent density values (Table 4) are higher than that of tree species of more humid forests (Pagotto et al. 2017). For the other two climax species, *Swietenia macrophylla* and *Cedrela odorata* of the Amazon Forest and Atlantic Forest, respectively, wood density was 0.81  $\text{g cm}^{-3}$  and 0.54  $\text{g cm}^{-3}$  (Alvarado et al. 2010; Anholetto 2013).

Possibly the variations in wood density were caused by climate changes and water availability (Balducci et al. 2014; Oliver et al. 2015). We observed density variations over time in all four species. In *Cariniana estrellensis*, there was an abrupt decrease near the pith. Thus, variations during tree growth may also influence the density through the radial section of the wood (Hietz et al. 2013). Generally, the proportion of juvenile wood, anatomically characterized by a



**Fig. 4** Radial variation of apparent tree density of *Schinus terebinthifolius*, *Peltophorum dubium*, *Cariniana estrellensis* and *Hymenaea courbaril*. Red circles show regions with greater density heterogeneity



higher proportion of early wood, with thin cell walls and larger lumens, decreases with tree aging, as wood density increases, a relatively frequent pattern of radial variation in native woods (Fearnside 1997a, b; Knapić et al. 2007).

Anatomical features such as the marginal parenchyma band also interfere with the wood densitometry profile, as verified in *Hymenaea courbaril*, in which the thin parenchyma band was characterized by a density of 0.80 g cm<sup>-3</sup>,

**Table 4** Average, minimum (min) and maximum (max) values of the apparent density obtained by X-ray densitometry of neotropical species used in forest restoration

Species	Average apparent density	Min–max density
<i>Schinus terebinthifolius</i>	0.65b	0.51–0.89
<i>Peltophorum dubium</i>	0.57c	0.34–0.98
<i>Cariniana estrellensis</i>	0.70a	0.38–0.89
<i>Hymenaea courbaril</i>	0.77a	0.46–0.99

Means followed by the same letter in the column did not differ according to Tukey's test ( $p < 0.05$ )

delimited by a region of higher density of  $1.10 \text{ g cm}^{-3}$  (Albuquerque et al. 2016). Another factor that may influence wood density variation is the core formation, that is, the deposition of extractives in the wood closest to the pith (Parolin 2002). The high density of the internal wood may reflect the investment in wood protection against rot, although it adds little to mechanical resistance (Hietz et al. 2013). Therefore, X-ray densitometry can also provide relevant information on the intra- and inter-annual density patterns of neotropical forest species and their functional significance within each successional class.

## Conclusions

We observed higher amplitudes of apparent density in the slow-growing species and the pattern of increase in the density from pith to bark was maintained for the species planted in the mixed forest restoration system. *Cariniana estrellensis* and *Hymenaea courbaril*, late secondary and climax species, respectively, had the highest density. Using X-ray densitometry, we determined characteristics such as minimum, average and maximum densities, and radial density variations, important for understanding the ecological functional role of successional classes of the neotropical forest.

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## References

ABNT [Associação Brasileira de Normas Técnicas] (1997) Projeto de Estruturas de Madeira: NBR 7190. Rio de Janeiro, ABNT, p 1–107

ABNT [Associação Brasileira de Normas Técnicas] (2003) Madeira—Determinação da densidade básica: NBR 11941. Rio de Janeiro, ABNT, p 1–6

Albuquerque AR, Castro VR, Lobão MS, Sarto C, Tomazello Filho M, Guedes FTP (2016) Comparative analysis of anatomy and microdensitometry of the growth rings of hardwoods and conifers, with emphasis on dendrochronology. *Sci For* 44(111):595–610

Alvarado JR, Tomazello Filho M, Pollito PAZ, Lobão MS (2010) Variação da densidade do lenho e relação com a largura dos anéis de crescimento de árvores de mogno, *Swietenia macrophylla*, da floresta tropical amazônica do Peru. *Sci For* 38(86):171–179

Amaral ACB, Tomazello Filho M (1998) Avaliação das características dos anéis de crescimento de *Pinus taeda* pela técnica de microdensitometria de raios-X. *Rev Ciência Tecnol* 6(12):17–23

Amazonas NT, Forrester DI, Silva CC, Almeida DRA, Rodrigues RR, Brancalion PHS (2018) High diversity mixed plantations of *Eucalyptus* and native trees: an interface between production and restoration for the tropics. *For Ecol Manag* 417(2):247–256

Anholetto Jr CR (2013) Dendroecologia e composição isotópica ( $\delta^{13}\text{C}$ ) dos anéis de crescimento de árvores de *Cedrela odorata*, Meliaceae, na Caatinga e Mata Atlântica do Estado de Sergipe. Dissertation Esalq-USP, p. 1–91. [https://teses.usp.br/teses/disponiveis/11/11150/tde-30102013-105715/publico/Claudio\\_Roberto\\_Anholetto\\_Junior.pdf](https://teses.usp.br/teses/disponiveis/11/11150/tde-30102013-105715/publico/Claudio_Roberto_Anholetto_Junior.pdf)

Balducci L, Deslauriers A, Giovannelli A, Beaulieu M, Delzon S, Rossil S, Rathgeber CBK (2014) How do drought and warming influence survival and wood traits of *Picea mariana* saplings? *J Exp Bot* 66:377–389

Beech E, Rivers M, Old Field S, Smith PP (2017) Global Tree Search: the first complete global database of tree species and country distributions. *J Sustain For* 36(5):454–489

Brancalion PHS, Chazdon RL (2017) Beyond hectares: four principles to guide re-forestation in the context of tropical forest and landscape restoration. *Restor Ecol* 25(4):491–496

Brancalion PHS, Viani RAG, Strassburg BBN, Rodrigues RR (2012) Finding the money for tropical forest restoration. *Unasylva* 63(239):41–50

Castro VRC, Tomazello Filho M, Surdi PG (2014) Avaliação do perfil radial do lenho de árvores de *Pinus (Pinus caribaea* var. *hondurensis* Barr. Et Golf) por densitometria de raios-X. *Sci For* 42(103):353–360

Chazdon RL (2008) Chance and determinism in tropical forest succession. In: Carson W, Schnitzer S (eds). *Tropical forest community ecology*. Wiley, p 384–409. [http://www.lerf.eco.br/img/publicacoes/2012\\_09%20Chance%20and%20Determinism%20in%20Tropical%20Forest%20Succession.pdf](http://www.lerf.eco.br/img/publicacoes/2012_09%20Chance%20and%20Determinism%20in%20Tropical%20Forest%20Succession.pdf)

Chazdon RL, Brancalion PHS, Lamb D, Laestadius L, Calmon M, Kumar C (2017) A policy-driven knowledge agenda for global forest and landscape restoration. *Conserv Lett* 10(1):125–132

Engel VL, Parrota JA (2001) An evaluation of direct seeding for reforestation of degraded lands in central São Paulo state, Brazil. *For Ecol Manag* 152:169–181

FAO (2016) *Global Forest Resources Assessment 2015. How are the world's forests changing?* FAO Forestry. Rome, p 1–54. <http://www.fao.org/3/a-i4793e.pdf>

Fearnside PM (1997a) Wood density for estimating forest biomass in Brazilian Amazonia. *For Ecol Manag* 90:59–87

Fearnside PM (1997b) Wood density for estimating forest biomass in Brazilian Amazonia. *For Ecol Manag* 90:59–87

Ferreira ATB, TomazelloFilho M (2009) Caracterização dos anéis de crescimento de árvores de *Pinus caribaea* var. *hondurensis* Barr. et Golf por densitometria de raios X. *Sci For* 37(83):287–298

Ferretti AR, Kageyama PY, Arbocz GF, Santos JD, Barros MIA, Lorza RF, Oliveira C (1995) Classificação das espécies arbóreas em grupos ecológicos para revegetação com nativas no estado de São Paulo. *Florest Est* 3(7):73–77

Gandolfi S, Leitão Filho HF, Bezerra CLF (1995) Estudo florístico e caráter sucessional das espécies arbustivo arbóreas de uma floresta mesófila semidecídua no município de Guarulhos SP. *Rev Bras Biol* 55(4):753–767

Hietz P, Valencia R, Wright SJ (2013) Strong radial variation in wood density follows a uniform pattern in two neotropical rain forests. *Funct. Ecol* 27:684–692

- Jankowsky IP, Chimelo JP, Cavalcante AA, Galina AM, Nagamura JCS (1990) Madeiras brasileiras. Spectrum, p 1–172. [http://www.scielo.br/scielo.php?script=sci\\_nlinks&ref=000113&pid=S0100-6762201400030001800018&lng=pt](http://www.scielo.br/scielo.php?script=sci_nlinks&ref=000113&pid=S0100-6762201400030001800018&lng=pt)
- Kelty MJ (2006) The role of species mixtures in plantation forestry. *For Ecol Manag* 233(3):195–204
- Knapic S, Louzada JL, Leal S, Pereira H (2007) Radial variation of wood density components and ring width in cork oak trees. *Ann For Sci* 64:211–218
- Lamb D (2005) Restoration of degraded tropical forest landscapes. *Science* 80(310):1628–1632
- Lima IL, Longui EL, Cerato C, Freitas MLM, Florsheim SMB, Zanatto ACS (2015) Basic specific gravity and anatomy of *Peltophorum dubium* wood as a function of provenance and radial position. *Rev Inst Flor* 27(1):19–29
- Lobão MS, Chagas MP, Costa DSP, Ferreira DTB, Sette Júnior CR, Carvalho IL, Tomazello Filho M (2010) Agrupamento de espécies florestais pela similaridade das características físico-anatômicas e usos da madeira. *Cerne* 16:97–105
- Moreira WS (1999) Relações entre propriedades físico-mecânicas e características anatômicas e químicas da madeira. Thesis, UFV, pp 1–199. <https://www.locus.ufv.br/bitstream/123456789/9167/1/texto%20completo.pdf>
- Nogueira Junior LR (2010) Estoque de carbono na fitomassa e mudanças nos atributos do solo em diferentes modelos de restauração da Mata Atlântica. Thesis, Esalq/USP, p 1–94. [https://teses.usp.br/teses/disponiveis/11/11150/tde-21102010-093438/publico/Lauro\\_Nogueira.pdf](https://teses.usp.br/teses/disponiveis/11/11150/tde-21102010-093438/publico/Lauro_Nogueira.pdf)
- Oliver J, Rathgeber C, Bravo F (2015) Climate change, tree-ring width and wood density of pines in Mediterranean environments. *IAWA J* 36(3):257–269
- Padilha DL, Marco Júnior P (2018) A gap in the woods: wood density knowledge as impediment to develop sustainable use in Atlantic Forest. *For Ecol Manag* 424(15):448–457
- Pagotto MA, De Soto L, Carvalho A, Nabais C, Tomazello Filho M, Ribeiro A, Lisi CS (2017) Evaluation of X-ray densitometry to identify tree-ring boundaries of two deciduous species from semi-arid forests in Brazil. *Dendrochronologia* 42:94–103
- Parolin P (2002) Radial gradients in wood specific gravity in trees of Central Amazonian floodplains. *IAWA J* 23(4):449–457
- Paula A, Silva AF, Marco Júnior P, Santos FAM, Souza AL (2004) Sucessão ecológica da vegetação arbórea em uma Floresta Estacional Semidecidual, Viçosa, MG, Brasil. *Acta Bot Bras* 18(3):407–423
- Piotto D (2008) A meta-analysis comparing tree growth in monocultures and mixed plantations. *For Ecol Manag* 255(3–4):781–786
- Quintek Measurement Systems (1999) QMS tree ring analyzer model QTRS-01X. Users Guide, Knoxville, pp 1–72
- R Core Team (2014) R: a language and environment for statistical computing. R foundation for statistical computing, p 1–2. <https://www.gbif.org/pt/tool/81287/r-a-language-and-environment-for-statistical-computing>
- Rezende MA, Escobedo JF, Ferraz ESB (1988) Retratibilidade volumétrica e densidade aparente da madeira em função da umidade. *IPEF* 39:33–40
- Rodrigues RR, Brancalion PHS, Isernhagen I (2009) Pacto pela restauração da mata atlântica: referencial dos conceitos e ações de restauração florestal. Instituto BioAtlântica, p 50–206 <http://www.lerf.esalq.usp.br/divulgacao/produtos/livros/pacto2009.pdf>
- Rodrigues RR, Gandolfi S, Nave AG, Aronson J, Barreto TE, Vidal CY, Brancalion PHS (2011) Large-scale ecological restoration of high diversity tropical forests in SE Brazil. *For Ecol Manag* 261:1605–1613
- Roque RM, Tomazello Filho M (2007) Relationships between anatomical features and intra-ring wood density profiles in *Gmelina arborea* applying x-ray densitometry. *Cerne* 13(4):384–392
- Santos SR, Sansígolo CA (2007) Influência da densidade básica da madeira de clones de *Eucalyptus grandis* x *Eucalyptus urophylla* na qualidade da polpa branqueada. *Ciência Florestal* 17(1):53–63. <http://www.scielo.br/pdf/cflo/v17n1/1980-5098-cflo-17-01-00053.pdf>
- Sette Júnior CR, Tomazello Filho M, Dias CTS, Chagas MP, Laclau JP (2009) Efeito da aplicação de potássio e sódio nas características do lenho de árvores de *Eucalyptus grandis* w.hill, aos 24 meses de idade. *Floresta* 39(3):535–546. <https://doi.org/10.5380/rf.v39i3.15353>
- Slik JWF, Arroyo-Rodríguez V, Aiba S-I, Alvarez-Loayza P, Alves LF, Ashton P, Balvanera P, Bastian ML, Bellingham PJ, van den Berg E, Bernacci L, Da Bispo PC, Blanc L, Böhning-Gaese K, Boeckx P, Bongers F, Boyle B, Bradford M, Brearley FQ, Hockemba MB-N, Bunyavejchewin S, Matos DCL, Castillo-Santiago M, Catharino ELM, Chai S-L, Chen Y, Colwell RK, Chazdon RL, Clark C, Clark DB, Clark DA, Culmsee H, Damas K, Dattaraja HS, Dauby G, Davidar P, DeWalt SJ, Doucet J-L, Duque A, Durigan G, Eichhorn KAO, Eisenlohr PV, Eler E, Ewango C, Farwig N, Feeley KJ, Ferreira L, Field R, Filho AT, De Fletcher OC, Forshed O, Franco G, Fredriksson G, Gillespie T, Gillet J-F, Amarnath G, Griffith DM, Grogan J, Gunatilleke N, Harris D, Harrison R, Hector A, Homeier J, Imai N, Itoh A, Jansen PA, Joly CA, de Jong BHJ, Kartawinata K, Kearsley E, Kelly DL, Kenfack D, Kessler M, Kitayama K, Kooyman R, Larney E, Laumonier Y, Laurance S, Laurance WF, Lawes MJ, DO Amaral IL, Letcher SG, Lindsell J, Lu X, Mansor A, Marjokorpi A, Martin EH, Meilby H, Melo FPL, Metcalfe DJ, Medjibe VP, Metzger JP, Mohandass JMD, Montero JC, De Valeriano MM, Mugerwa B, Nagamasu H, Nilus R, Ochoa-Gaona S, Onrizal PN, Parolin P, Parren M, Parthasarathy N, Paudel E, Permana A, Piedade MTF, Pitman NCA, Poorter L, Poulsen AD, Poulsen J, Powers J, Prasad RC, Puyravaud J-P, Razafimahaimodison J-C, Reitsma J, dos Santos JR, Spironello WR, Romero-Saltos H, Rovero F, Rozak AH, Ruokolainen K, Rutishauser E, Saiter F, Saner P, Santos BA, Santos F, Sarker SK, Satdichanh M, Schmitt CB, Schöngart J, Schulze M, Suganuma MS, Sheil D, Pinheiro E, De Sist SP, Stevart T, Sukumar R, Sun IF, Sunderland T, Suresh HS, Suzuki E, Tabarelli M, Tang J, Targhetta N, Theilade I, Thomas DW, Tchouto P, Hurtado J, Valencia R, van Valkenburg JLCH, Do Van Vasquez TR, Verbeeck H, Adekunle V, Vieira SA, Webb CO, Whitfield T, Wich SA, Williams J, Wittmann F, Wöll H, Yang X, Yao CYA, Yap SL, Yoneda T, Zahawi RA, Zakaria R, Zang R, de Assis RL, Luize BG, Venticinque EM (2015) An estimate of the number of tropical tree species. *Appl Biol Sci Environ Sci* 112(33):4628–4629
- Sos Mata Atlântica Fundação (2015) Atlas dos Remanescentes Florestais da Mata Atlântica—Período 2013–2014. Fundação SOS Mata Atlântica, p 3–60p. <https://www.sosma.org.br/wp-content/uploads/2019/06/Atlas-mata-atlanticaDIGITAL.pdf>
- Souza VR, Carpim MA, Barrichelo LEG (1986) Densidade básica entre procedências, classes de diâmetro e posição em árvores de *Eucalyptus grandis* e *Eucalyptus saligna*. *IPEF* 3:63–72
- Stape JL, Gandara FB, Santos JD, Gusson E, Mendes JCT (2006) Modelos de recuperação de áreas degradadas da Mata Atlântica com espécies nativas em duas regiões do Brasil visando o sequestro de carbono. Petrobrás Project Final Report, p 10–164. <https://www.ipef.br/pesquisas/>
- Swaine MD, Whitmore TC (1988) On the definition of ecological species groups in tropical rain forests. *Vegetatio* 75(1–2):81–86
- Thorntwaite CW, Mather JC (1955) The water balance. Centeron: Drexel Institute of Technology, Philadelphia, p 1–104. [http://www.scielo.br/scielo.php?script=sci\\_nlinks&ref=000064&pid=S0006-8705200500020001900006&lng=pt](http://www.scielo.br/scielo.php?script=sci_nlinks&ref=000064&pid=S0006-8705200500020001900006&lng=pt)
- Tomazello Filho M, Botosso PC, Lisi CS (2001) Análise e aplicação dos anéis de crescimento das árvores como indicadores



- ambientais: dendrocronologia e dendroclimatologia. In: Indicadores ambientais: conceitos e aplicações. EDUC Ed, p 1–143
- Tomazello Filho M, Chagas MP, Roque RM (2005) Manual de aplicação de densitometria de raios-X em amostras de madeira, CRAD e CERD. Fealq Ed, p 1–32 p
- Tomazello Filho M, Brazolin S, Chagas MP, Oliveira JTS, Ballarin AW, Benjamin CA (2008) Application of X-ray technique in non-destructive evaluation of Eucalypt wood. *Maderas Ciênc Tecnol* 10(2):139–145
- Vivian MA, Modes KS, Beltrame R, Souza JT, Santini EJ, Haselein CR (2010) Propriedades físico-mecânicas da madeira de canafístula aos 10 anos de idade. *Ciênc Rural* 40(5):1097–1102
- Xavier CN (2016) Avaliação não destrutiva da qualidade da madeira e do fuste de árvores de *Peltophorum dubium* (Spreng.) Taub em área de restauração florestal. Dissertation, Federal Rural University of Rio de Janeiro, p 1–69 <https://tede.ufrjr.br/jspui/handle/jspui/1362>

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