

Wood density of loblolly pine trees as affected by crown thinnings and harvest age in southern Brazil

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Abstract The Brazilian plantation forestry is well known for high yields. Such yields are not necessarily linked with acceptable wood quality. Pine plantations are an important source of timber in Brazil, and although pulp and paper production plays a dominant role, there is an increasing need for sawtimber, and even high-quality timber is in demand. The impacts of crown thinning on ring width, ring density and juvenile–mature wood of loblolly pine trees were analysed. The experimental design included no thinning, an extreme release from competition, and two practice-oriented variants with moderate and heavy thinnings. X-ray microdensitometry provided ring width and density for 1197 rings and 44 trees. Mean ring width at 1.3 m height varied from 6 to 9 mm, reaching a maximum of 22 mm during the first 3–6 years regardless of thinning intensity. Only occasional differences were verified in ring densities produced from the different thinning variants. The transition from juvenile to mature wood occurred between 13 and 17 years of age. From the analysis of wood density, extreme and early thinning delayed the production of mature wood in ~ 4 years compared with non-thinned or practice-oriented thinned stands. At the same harvest age, thinning had no effect on wood density. However, harvest age itself was a determinant for obtaining wood of higher density. Altogether, results indicated that regarding current market demands no constraints related to the

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analysed wood characteristics are to be expected, even if extreme thinning regimes are applied.

Introduction

Pine plantations cover ~ 1.6 million hectares in Brazil (IBÁ 2016) and are managed almost completely according to relatively short rotation schemes of 15–20 years. Although pulp and paper production plays the dominant role, there is an increasing need of timber for solid end-uses. However, the global trend of short harvest ages has led to concerns about the quality of the timber produced (Walker 1993; Larson et al. 2001; Barbour et al. 2003; Oliveira et al. 2006; Schneider et al. 2008).

The term ‘wood quality’ strongly depends on the particular end-use of the wood (Smith and Briggs 1986). Several criteria can be regarded to assess wood quality, of which wood density is considered an important one (Megraw 1985; Guilley et al. 1999; Koubaa et al. 2002; Jyske et al. 2008). Wood quality of conifers is the result of the annual growth ring structure: ring width, early- and latewood distribution and the juvenile–mature wood proportion within a radial segment described below:

- Ring width is the parameter most frequently used to assess the stem growth rate. However, its formation pattern and uniformity are of greater interest than growth rate when assessing wood quality.
- The early- and latewood proportions in the stem follow the seasonal patterns of crown development (Larson 1962, 1969; Megraw 1985). This is a physiological process and depends on the vigour and growth conditions of the tree (Larson 1962). The proportion of latewood within a growth ring helps to define the type of wood that was formed (Hennessey et al. 2004).
- Juvenile wood is produced under strong influence of the cambial age, produced at the uppermost part of the tree crown (Larson 1972; Megraw 1985; Smith and Briggs 1986; Alteyrac et al. 2006). Thus, the term ‘juvenile wood’ describes the type of wood produced in young trees. Nevertheless, the same or a very similar type of wood is also produced in the rings nearest the pith at all heights in the stem (Larson 1969; Zobel and Jett 1995).

Some of the characteristics of the timber depend on the proportion of juvenile wood and size of the juvenile core within the log (Gartner 2005; Alteyrac et al. 2006). This is because juvenile wood is, compared to mature wood, characterised by the following (Zobel 1981; Smith and Briggs 1986; Kretschmann and Bendtsen 1992; Macdonald and Hubert 2002; Ballarin and Palma 2003; Mead 2013):

- lower density (15–30%);
- shorter tracheids (increasing ~ 60% until mature wood starts to be formed);
- lower strength and stiffness (~ 50% lower in the juvenile wood);
- lower-dimensional stability;
- higher microfibril angle.

Intensively managed plantations deliver timber with a higher proportion of juvenile wood compared to that harvested from older stands (Clark et al. 2006). Although juvenile wood can be tolerated for some industrial uses (Zobel and Sprague 1998; Gartner 2005), it is undesirable for solid end-uses (Macdonald and Hubert 2002; Barbour et al. 2003; Alteyrac et al. 2006).

Timber produced from young stems with a disproportionately high percentage of juvenile wood is less suitable for construction purposes. This is due to the modulus of rupture, which is commonly lower for juvenile wood (Senft et al. 1985; Smith and Briggs 1986; Kretschmann and Bendtsen 1992). The consensus is that juvenile wood is undesirable for products requiring stability and strength.

Although loblolly pine is the most planted conifer in Brazil, little is known about the wood quality from older plantations, and long-term studies with stands submitted to extreme thinning regimes are even rarer. The influences of crown thinning on wood quality were analysed. The specific objectives were

- to investigate patterns of ring width,
- to determine the radial variation in wood density (ring average density, late-wood density and latewood proportion),
- to estimate the beginning of mature wood production and, thus, quantify its proportion with respect to the different thinning regimes, and
- to evaluate the influence of harvest age on wood density.

This article is part of a broader project, which was carried out with the goal of analysing a long-term field study concerning the effects of thinnings of loblolly pines from different perspectives. One of them, wood quality, is reported here.

Materials and methods

Trees analysed in this study grew in southern Brazil, where the climate is humid and subtropical, with ~ 1800 mm rainfall well distributed during the entire year. Soils are rich and of volcanic origin. The thinning trial was designed by Prof. Dr. Dr. h.c. Jürgen Huss and established in 1986 in a 5-year-old loblolly pine stand (7–8 m in height). The experimental design included a gradient of four thinning variants (Table 1), in which 400 potential crop trees ha⁻¹ were selected and released from competition in different intensities by removing competitor trees (crown thinning). Later on, thinning continued by removing a certain number of competitors and by reducing the number of potential crop trees in the ‘extreme’ variant.

Small inconsistencies in the number of trees per hectare after thinning were due to some differences in initial stand density and because values were rounded. In any case, the number of competitors removed per potential crop tree is most important.

Thinning variants were established in ~ 0.2 ha plots (~ 0.1 ha of effective area), randomly distributed in 2 blocks. At 30 years of age, the experiment was terminated. Selected trees were harvested, and cross-sectional discs were sampled at 1.3 m.

Table 1 Thinning programme as characterised by the number of remaining trees (remain.) and the number of competitors (comp.) that were eliminated in order to favour the potential crop tree candidates and, finally, the potential crop trees

Age (years)	Thinning variant							
	Without		Moderate		Heavy		Extreme	
	Remain.	Comp.	Remain.	Comp.	Remain.	Comp.	Remain.	Comp.
0	2500		2500		2500		2500	
5	All	–	2100	1	1700	2	400	All
7	All	–	1700	1	1300	1	400	–
10	All	–	1300	1	900	1	250	0.4
13	All	–	800	1	500	1	150	0.4
15	All	–	400	1	500	–	150	–

Data collection

Tree sampling regarded the whole diameter range within thinning variants, thus being representative and representing different growth rates. In total, 12 trees were collected per thinning variant (6 per plot), except for the ‘extreme’ variant, where only eight trees were sampled because of wind damages ~ 1 year previous to the present analysis. The quadratic mean diameter (d_g) at 30 years of age as well as the minimum and maximum diameters of sampled trees within thinning variants is listed in Table 2.

Altogether, 44 trees were sampled. Wood samples were taken from the cross-sectional discs at 1.3 m, excluding whorls and defects.

Determination of wood density

Wood density analyses included the following steps:

- Cutting of wood samples using a twin-bladed circular saw (10 mm in height and $1.7 \text{ mm} \pm 0.02 \text{ mm}$ in width). A radial segment from pith to bark was removed.

Table 2 Quadratic diameter (d_g), minimum and maximum diameter values of sampled trees within the different thinning variants at 30 years of age

Thinning variant	Diameter (cm)	
	d_g (cm)	Minimum–Maximum
Without	35.6	20–61
Moderate	45.8	26–68
Heavy	48.8	32–71
Extreme	61.9	43–76

- Wood specimens were kept for ≥ 24 h at a stable air humidity of 60% and temperature of 20 °C = stabilised moisture of 12%, thus delivering apparent density values. Procedure was described by Amaral and Tomazello (1998).
- Scanning of the wood strips using a direct X-ray microdensitometer (QTRS-01X, Quintek Measurement Systems Inc. Knoxville, TN) integrated with a computer analysis system.
- Determination of wood density based on the relationship of X-ray attenuation. The mass attenuation coefficient is a material property and depends upon the energy of incident radiation (voltage from 10 to 50 kV, maximum current of 1.5 mA) and the material composition.
- Calculation of annual ring density as the mean of 2 radii per tree.
- Adjusting of a fixed threshold density at 0.550 g cm^{-3} (Koubaa et al. 2002); thus, values above and below represented the late- and earlywood, allowing ring-width delimitation.

Data analysis

Because the discs were taken at 1.3 m above ground, the annual growth rings corresponding to the first 2 years of the trees' live were not always present. Thus, density analysis started from the third annual growth ring onward.

To analyse the data and assure the absence of X-ray reading errors, density profiles were built and fitted with the image of the respective wood sample.

Using the threshold of 0.550 g cm^{-3} , annual growth rings were defined and their widths determined. On average, the differences between ring-width measurements through X-rays and digitalised cross-sectional discs were ± 0.1 mm, or $\pm 1.5\%$. The results indicated that both methods were accurate.

Graphical representations of mean ring density per thinning variant were used to analyse their development over time. The age of transition from juvenile to mature wood was determined by visual interpretation of these graphs by considering the moment at which density showed a levelling-off trend. It was also determined by evaluating the development of latewood density and proportion. Values $\geq 0.550 \text{ g cm}^{-3}$ for density and $\geq 50\%$ for latewood proportion were utilised for these purposes (Clark et al. 2006).

Differences between thinning variants were evaluated for the following variables:

- ring width (mm),
- mean, minimum, and maximum ring densities (g cm^{-3}),
- wood density (an average value for the entire radial segment),
- latewood density (g cm^{-3}),
- latewood proportion (%), and
- juvenile and mature wood width and proportion.

The wood density was averaged from growth rings up to ages of 10, 15, 20, 25 and 30 years (beginning with the third ring). Thus, the influence of harvest age on the density was evaluated, within and between thinning variants.

The relationship between wood density and ring width is also shown.

Statistical analyses were based on a fully randomised design, in which observations were pseudo-replicated. Trees were sampled within the two plots of each thinning variant (i.e. trees were not totally independent observations). However, this approach was supported by the homogeneity of the study area, evidenced through a lack of block effect for stand growth analysis. Levene tests were performed prior to analysis of variance (ANOVA), and they confirmed the variance homogeneity of the data set.

Probability (p) values of the ANOVA for each tested parameter are given. After detecting significant differences with ANOVA, means were classified with letters according to the Tukey's test, in which values with the same letter do not significantly differ. The lowest value received the letter 'a'. Small letters indicate differences between thinning variants (columns), while capital letters show differences within thinning variants (line).

Results

Ring width

The ring widths formed by the trees in the different thinning variants are listed in Table 3.

In Table 3, it can be verified that the mean ring width varied according to the thinning intensity. Trees in the non-thinned stand showed the lowest value, followed by the practice-oriented variants ('moderate' and 'heavy'), which produced rings of similar widths. Trees in the 'extreme' variant produced, on average, the widest growth rings.

From age 13–17 years onward, depending on thinning intensity, trees started producing mature wood. Although the analysis of juvenile and mature wood is discussed in detail below, it could be verified that the average ring width formed

Table 3 Mean and maximum ring widths with respect to the entire analysed period (age 3–30 years) for the different thinning variants and mean ring width formed during the mature phase (~ 15–30 years)

Thinning variant	Ring width (mm)		
	Mean	Maximum	Mean mature
Without	5.7a	21.7a	2.5a
Moderate	7.1b	21.9a	4.1b
Heavy	7.5b	22.3a	3.8b
Extreme	9.4c	22.7a	5.0b
p	< 0.001	0.833	< 0.001

Ring-width data with the same letter are not significantly different at $p \leq 0.05$

during the mature period was similar between thinned variants, all of them with wider growth rings than the stand without thinning.

Ring density

The ring densities per growth ring as formed for the different thinning variants are shown in Fig. 1.

A consistent pattern of increasing ring density with age was observed, characterised by a rapid progression that levelled off at 0.550 g cm^{-3} . The highest decrease in ring density was observed at age 28 years probably because of a drought phase. This was long after those ages at which thinning took place and, therefore, not related to them.

In general, a numerical superiority was observed in the ring densities produced by the trees without thinning. Only occasional differences were detected among years, at ages 11, 14, 22, and 25 years, when the density of rings produced in the control (without thinning) was similar to the practice-oriented variants ('moderate' and 'heavy') but higher than the one observed in the 'extreme'.

Mean ring density, coefficient of variation, minimum and maximum values regarding individual ring values are listed in Table 4.

No differences between thinning variants were detected for mean, minimum and maximum densities regarding growth ring values among the 30-year period (Table 4). However, the coefficient of variation of the wood density indicated that the rings formed in the thinned variants were more homogenous than the ones produced in the stands without thinning.

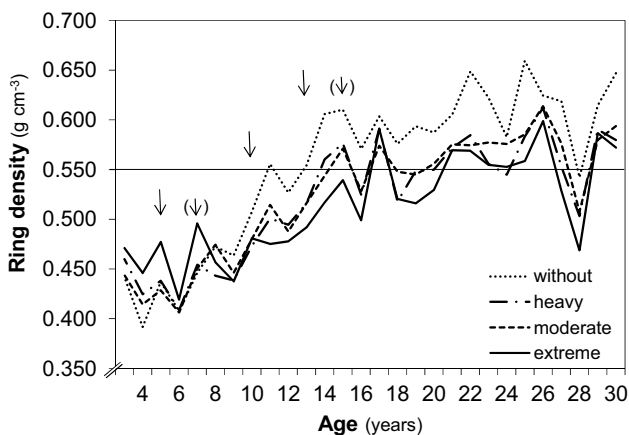


Fig. 1 Ring densities within the different thinning variants during the years of the study. Arrows indicate the year at which thinning took place; arrows in parentheses mean only some of the variants were thinned at the following ages: 7 years = moderate and heavy; 15 years = moderate

Table 4 Mean, minimum and maximum ring density (g cm^{-3}) and the coefficient of variation related to the mean values for the different thinning variants during the studied period (3–30 years)

Thinning variant	Ring density (g cm^{-3})			Coefficient of variation (%)
	Mean	Minimum	Maximum	
Without	0.550a	0.380a	0.710a	16.4b
Moderate	0.520a	0.390a	0.650a	13.5a
Heavy	0.520a	0.390a	0.640a	13.5a
Extreme	0.510a	0.410a	0.640a	11.8a
<i>p</i>	0.164	0.078	0.082	0.002

Values are rounded to the nearest tenth. Min. = growth ring with the lowest average density. Max. = growth ring with the highest average density. Values with the same letter are not significantly different at $p \leq 0.05$

Juvenile and mature wood

The transition from juvenile to mature wood occurs gradually. It is known that mature wood is being formed when ring density, latewood density and per cent latewood stabilise.

One approach is related to mean ring density (Fig. 1). The data show that the transition from juvenile to mature wood occurred between the 10th–17th growth ring for all treatments when ring density levelled off around 0.550 g cm^{-3} first for the trees without thinning and last for the ones in the ‘extreme’.

The latewood densities and latewood percentages per growth ring are shown in Figs. 2 and 3, respectively. Both are important in supporting conclusions about the transition age from juvenile to mature wood.

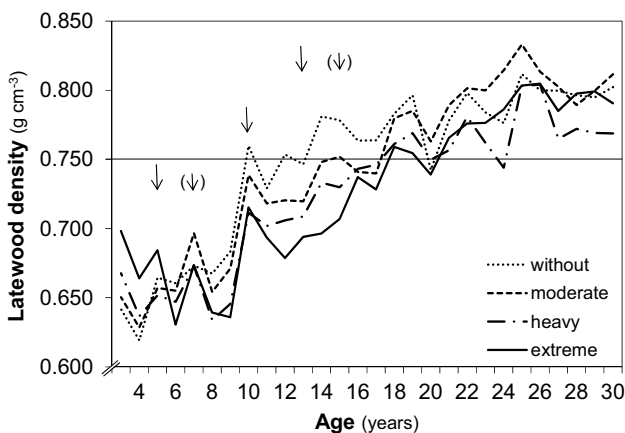


Fig. 2 Latewood density formed by trees in the different thinning variants over time. Arrows indicate the year at which thinning took place; arrows in parentheses notify that in only some of the variants thinning took place at ages: 7 years = moderate and heavy; 15 years = moderate

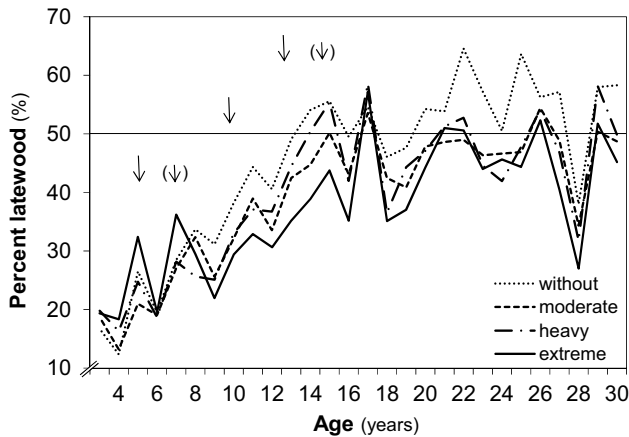


Fig. 3 Latewood per cent of rings formed in the different thinning variants along time. Arrows indicate the year during which thinning took place; arrows in parentheses mean only some of the treatments were thinned at ages: 7 years = moderate and heavy; 15 years = moderate

Conclusions about the transition age from the latewood density analysis were similar to those obtained from the mean ring density (Fig. 1). Latewood densities of trees without thinning levelled off by age 10–12 years, although thinned stands took 3–6 more years to reach the 0.750-g cm^{-3} density level. More important than the value 0.750 g cm^{-3} is the levelling-off pattern.

Significant differences in latewood densities between thinning variants were detected for ages 12, 14 and 15 years, when the values of the trees in the ‘extreme’ variant were lower than the ones measured in the stands without thinning. In all cases when differences were detected, the practice-oriented variants showed similar values to the ones verified in the control.

In Fig. 3, a levelling-off trend at $\sim 50\%$ in the latewood per cent of rings can be observed. Again, more important than the 50% value is the stabilisation pattern. It occurred earlier in the stands without thinning, at age 13 years, while trees in the ‘extreme’ reached this level and, therefore, stabilised around the age of 17 years.

In general, the results suggest that the early and ‘extreme’ release from competition would cause a longer period of juvenile wood production. While the stands without thinning and the practice-oriented ones started producing mature wood at about the same age (~ 13 years), the stands with ‘extreme’ thinning started only at age ~ 17 years onward. Therefore, to be conservative, for practical reasons and for the further analyses, it was defined that treatments started producing mature wood from ages of

- 13 years for the trees in the thinning variants ‘without’, ‘moderate’, and ‘heavy’ and
- 17 years for trees in the ‘extreme’ one.

Table 5 Mean densities (g cm^{-3}) of juvenile and mature wood of the different thinning variants

Thinning variant	Density		<i>p</i>
	Juvenile	Mature	
Without	0.460A	0.610B	<0.001
Moderate	0.460A	0.560B	<0.001
Heavy	0.450A	0.560B	<0.001
Extreme	0.480A	0.550B	<0.001
<i>p</i>	0.419	0.054	

Density values are rounded to the nearest tenth. Means with the same letter are not significantly different at $p \leq 0.05$. Means with the same capital letter do not significantly differ within treatments

Table 6 Width and proportion of juvenile wood and mature wood width per thinning variant

Thinning variant	Juvenile wood		Mature wood (cm)
	Width (cm)	Proportion (%)	
Without	21a	71b	9a
Moderate	24a	61a	16b
Heavy	27a	66ab	15b
Extreme	41b	77b	13ab
<i>p</i>	< 0.001	0.002	0.002

Juvenile width or juvenile core is equal to twice the juvenile radius. Means with the same letter are not significantly different at $p \leq 0.05$. Italic values indicate percentages

Thus, juvenile and mature wood densities were quantified. Results are listed in Table 5.

In Table 5, both the juvenile and mature wood have similar densities among treatments. However, as expected within treatments, mature wood was significantly denser than juvenile wood.

After defining the age when mature wood production began, it was also possible to determine its dimensions. Average width and proportion of juvenile wood as well as mature wood width for the thinning variants are listed in Table 6.

In Table 6, it can be observed that the juvenile wood core was smallest in the trees without thinning, which were similar to the ones obtained in the practice-oriented variants. Trees in the ‘extreme’ variant produced significantly bigger juvenile cores, twofold greater than the ones obtained in the controls. However, by comparing the proportion in relation to tree diameter at age 30 years, the ‘moderate’ variant showed the lowest value, similar to the one observed in the ‘heavy’ variant. In relative terms, trees in the controls produced a juvenile wood core equally as large as the ‘extreme’ ones.

Although smaller juvenile wood cores in absolute terms were produced in the control plots, they produced the smallest mature wood width due to the low growth rate during the second half of the analysed period. Trees in the practice-oriented variants delivered the biggest mature wood layers. In the ‘extreme’

variant, mature wood layers were similar to both practice-oriented and ‘without’ ones as a result of postponed production of mature wood (from age 17 years onward). It is important to note that differences between thinning variants are greater when the area of mature wood is considered, and they are larger with respect to volume.

Wood density according to ring width

The ring density plotted over the ring width is given in Fig. 4. The classification of mature and juvenile wood formation was carried out according to the analyses previously shown.

A general trend of decreasing ring density with increasing ring width is observed in Fig. 4, regardless of thinning intensity. The correlation between ring width and wood density explained by the coefficient of determination (R^2) shows intermediate values (0.44–0.49). It can also be observed that thinning decreases the slope of this trend. Slope coefficients were lower the more intense the thinning (-0.012 to -0.007).

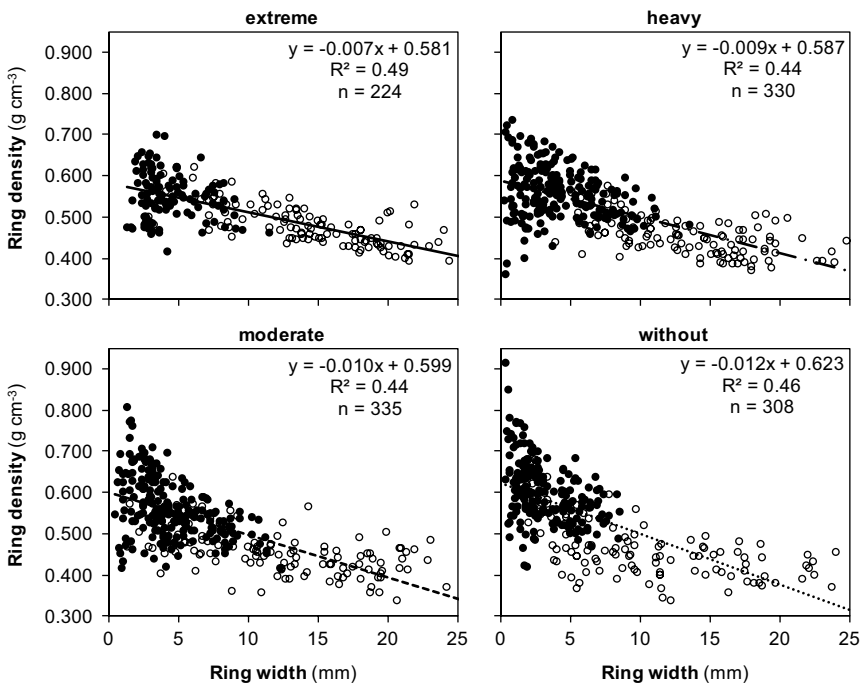


Fig. 4 Ring density according to the ring width. Black circles indicate the rings formed during the mature phase, while the white ones were formed during the juvenile period. Equations of the linear trend, their coefficient of determination (R^2) and number of observations (n) are given

Although very heterogeneous, the density of rings formed during the mature phase was mainly denser than the ones formed during the juvenile phase, as already verified by the previous analyses.

Wood density according to harvest age

To evaluate the influence of harvest age on the wood density, mean wood densities of the first 10, 15, 20, 25 and 30 annual growth rings were grouped and compared within and between thinning variants (Table 7). Periods included growth rings from age 3 years onward.

Considering the same harvest age for all thinning variants, similar wood densities were obtained (Table 7). The previous conclusion that thinning intensity does not influence wood density was reinforced. However, within thinning variants, increasing harvest age was a determinant for obtaining timber with higher density. Nevertheless, by harvesting trees at 20 years of age, similar mean wood densities can be obtained to the ones at age 30 years.

Discussion

Prior to discussing the results, a critical examination of the X-ray measurements accuracy is needed. According to Jacquin et al. (2017), in recent years, 67% of the studies related to wood densitometry were carried out with radiography-based devices, which provide reliable measurements. The device used in the present study is one of the three most popular ones, all of them with a comparably good accuracy (about $50 \mu\text{m pixel}^{-1}$). In addition, previous studies support the approach regarded of defining ring thresholds, or the latewood–earlywood transition, as being abrupt and defined by a value of wood density, especially for *P. taeda* (Eberhardt and Samuelson 2015).

Table 7 Mean densities (g cm^{-3}) according to harvest age for the thinning variants

Thinning variant	Harvest age (years)					<i>p</i>
	10	15	20	25	30	
Without	0.450A	0.490AB	0.520BC	0.540BC	0.550C	< 0.001
Moderate	0.440A	0.480AB	0.500C	0.510C	0.520C	< 0.001
Heavy	0.440A	0.480AB	0.500BC	0.510BC	0.520C	< 0.001
Extreme	0.460A	0.480A	0.490AB	0.510B	0.510B	0.007
<i>p</i>	0.583	0.552	0.353	0.206	0.164	

Density values are rounded to the nearest tenth. Means with the same letter are not significantly different at $p \leq 0.05$. Capital letters indicate differences in harvest age within the same thinning variant

Growth ring characterisation

Growth ring delimitation was performed using a threshold (Clark et al. 2006; Antony et al. 2012). Values from 0.400 to 0.550 g cm⁻³ are given in the literature (Koubaa et al. 2002). For loblolly pine grown in North Carolina, USA, Antony et al. (2012) reported that 0.480 g cm⁻³ is a suitable value.

For the analysed trees and after testing, it was concluded that 0.550 g cm⁻³ accurately delimited the boundary of early- to latewood and vice versa. This conclusion was based on previous ring measurements, which resulted in similar ring widths compared to those obtained with the defined threshold above.

Ring width

Regarding wood quality, the analysis of ring width is used as a grade index in some markets. According to Castillo et al. (2000), timber for structural uses in the USA should have rings no wider than 6 mm. A similar value was reported by Krahmer (1986), but with a maximum width of 4 mm per ring.

Although growth ring width alone is not necessarily related to wood strength, wide rings are often associated with juvenile wood, i.e. a low proportion of latewood. According to Dickens and Moorhead (2005), these 6- and 4-mm rules, in fact, only make sense when they are related to the amount of latewood:

- 6-mm rings with $\geq 1/3$ of latewood per ring or
- 4-mm rings with $\geq 1/2$ of latewood.

Pollet et al. (2017) analysed the effect of growth rate on the physical and mechanical properties of Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and concluded that, from a technological standpoint, maintaining mean ring width under 4 mm in juvenile wood and 6 mm in mature wood should accommodate all potential uses of this species.

In this study, mean ring widths varied between 6 and 9 mm, which were observed in the ‘without’ and ‘extreme’ treatments, respectively. Ring width reached maximum values of 22 mm, which was similar for all thinning variants formed during the first 3–6 years of trees’ live.

According to Dickens and Moorhead (2005), there are some wood products, generally the most valuable ones, for which the ring width is valued because of aesthetic reasons. According to Koch (1972), wide rings may affect attractiveness, paint retention, gluing characteristics and machinability of wood products.

The mean ring widths of the mature wood production phase were between 2 and 5 mm, which were observed in ‘without’ and ‘extreme’ thinning treatments, respectively. Although significantly lower in the control (Table 3), all of them allow high-quality end-uses according to the rules cited above, whenever strength or decorative purposes are needed, provided the timber is free of knots and other

defects. Although not regarded in this study, as mentioned by Biblis et al. (2004), knot size and knot location are obviously important features in this context.

Ring density

Regarding growth ring individual values, the mean density during the 30-year period was 0.530 g cm^{-3} , which was similar among treatments and comparable to previous studies with loblolly pine. Einspahr et al. (1964) reported values of 0.499 g cm^{-3} . Lower values (0.366 g cm^{-3}) for 13-year-old trees were found by Higa et al. (1973). Higher values were measured by Ballarin and Palma (2003) (0.605 g cm^{-3} for 37-year-old trees), indicating that density is a feature driven by cambial age.

In this study, density reductions occurred following thinning at ages 5 and 7 years (Fig. 1). The ‘moderate’, ‘heavy’ and ‘extreme’ treatments showed reductions of 5, 7 and 13%, respectively, in wood density confined to the first subsequent annual ring after the first thinning. Although it might show a trend of decreasing density with increasing thinning intensity, a decrease of 7% in density at the same year on the trees in the controls indicates that other factors might have been involved (i.e. weather conditions).

Punctuated differences between the wood densities produced in the thinning variants were observed. The growth ring densities formed in trees subjected to the control variant were sometimes higher than those after ‘extreme’ thinnings. However, no long-term implications were detected. Moreover, the rings formed in the practice-oriented variants did not differ from those formed in the controls.

In fact, no differences between the wood density produced under all tested conditions were detected when mean (over the entire radius), minimum and maximum ring densities were compared (Table 4). The punctuated lower densities observed in the ‘extreme’ variant might have been caused by greater crown vigour of the trees, which were completely devoid of competition and, therefore, forming wider and deeper crowns. According to Megraw (1985), extreme crown vigour may slightly negatively influence wood density by prolonging earlywood or intermediate cell production.

It is worth noting that the coefficient of variation of the wood density produced in the thinned variants was significantly lower than in the stands without thinning, indicating that a more homogenous wood was produced due to thinning, regardless of intensity (Table 4).

In previous studies, contradictory results regarding the influence of thinning on wood density are reported. While some authors found no effects of widely spacing on wood density (Megraw 1985; Zhang et al. 1996; Tasissa and Burkhart 1998a; Peltola et al. 2007; Vincent et al. 2011; Blazier et al. 2013), others reported lower (Barbour et al. 1994; Koubaa et al. 2000; Kang et al. 2004, Todaro and Macchioni 2011) or even higher densities (Guller et al. 2012) in non-thinned stands.

This contradiction was deeply discussed by Megraw (1985). The author reported that some misunderstandings occurred, as wood from different cambial ages has been compared. This was also recently reported by Ivković et al. (2013).

It was found that ring density was only punctually reduced following thinning and can be expected to be undetectable when mean values over an entire radial segment are evaluated. This happens because effects of silvicultural treatments generally have a short-term effect on wood density (Mora et al. 2007). Results were in line with previous reports (Megraw 1985; Peltola et al. 2007; Vincent et al. 2011; Blazier et al. 2013).

Although very heterogeneous, rings formed during the mature phase had a clear higher-density level than the ones formed during the juvenile phase (Fig. 4). It is important to note that, during the mature phase, trees in the ‘extreme’ variant grew twice as much as the ones in the stand ‘without’ thinning, even though no differences in mean wood density were detected (Table 4).

According to Megraw (1985), wood densities and growth rates are independent traits for coniferous trees of comparable environments when considering equal age and height level. Additionally, Senft et al. (1985) noted that there is overwhelming evidence that wood density and growth rate are not always correlated.

In fact, if coniferous individuals are encouraged by thinning to grow more rapidly, they produce a greater volume of the same kind of wood than those without any intervention (Shepherd 1986; Smith et al. 1997). Consequently, a mature tree will continue to form high-quality wood despite a relative increase in growth rate following heavy thinning (Larson 1969).

According to Tasissa and Burkhart (1997), one explanation for this is that wide growth rings show a proportional increase in early- and latewood. Thus, no differences in wood density after thinning can be detected. Similarly, Kantavichai et al. (2010) reported that thinning increased latewood width but did not affect ring density of Douglas fir in western Washington, USA.

Differences in wood densities of conifers are more likely related to site quality (climate and soil). The wood produced on better sites is denser, even though the trees grow faster (Megraw 1985; Jokela et al. 2004). According to Clark et al. (2006), a lower competition level among trees provides more moisture for the trees, and when water is a limiting factor in late summer, it favours the latewood formation. For loblolly pine, increasing soil water availability via irrigation increased wood density and latewood percentage by 0.036 g cm^{-3} , or 7% (Gonzalez-Benecke et al. 2010).

At ages 17 and 28 years, a clear peak and valley in ring density were observed, respectively. The explanation for this is precipitation. At age 17 years, there was twice as much precipitation (850 mm) during late summer (February–April) in comparison with the average for the whole 30-year period (415 mm). Oppositely, at age 28 years, late summer has only half of the precipitation (240 mm). Although a clear relationship between precipitation during late summer and ring density could be observed, further studies on this are needed for a deeper understanding of climate and loblolly pine growth in southern Brazil.

Juvenile and mature wood

The transition from juvenile to mature wood is not confined to a single year, but occurs gradually (Macdonald and Hubert 2002; Alteyrac et al. 2006; Clark et al.

2006; Mead 2013). However, by evaluating combinations with features like ring density, latewood density and latewood per cent, and after these features showed a levelling-off trend, it is possible to identify the moment at which mature wood is being formed. From a practical perspective, the characterisation of the transition is needed to understand the effects of silvicultural treatments on wood quality (Mora et al. 2007). According to Kretschmann and Bendtsen (1992), the segregation of juvenile and mature wood is the most important criterion related to wood strength for loblolly pine plantations in the USA.

The transition between juvenile to mature wood typically occurs between 5 and 20 years of age (Shepherd 1986; Zobel and Sprague 1998; Castillo et al. 2000; Ballarin and Palma 2003; Clark et al. 2006; Mora et al. 2007; Guller et al. 2012; Mead 2013; Palermo et al. 2013). For loblolly pine, 11–13 years of age has been reported (Zobel 1981; Krahmer 1986; Tasissa and Burkhart 1998b; Hennessey et al. 2004; Pauleski 2010).

A graphical analysis of the ring density development along years showed that the transition from juvenile to mature wood occurred in the period between the 10th and the 17th year (Fig. 1).

According to Alteyrac et al. (2006), the use of latewood density is another suitable criterion to determine the boundary between juvenile and mature wood. When the latewood density was considered, the levelling-off trend was observed at age 10, 16 and 18 years for the ‘without’-, ‘practice-oriented’-, and ‘extreme’-thinned stands (Fig. 2).

When the latewood proportion of loblolly pine comprises more than 50% of the growth ring, it is assumed that mature wood is being produced (Hennessey et al. 2004). With this criterion, trees in the control started forming mature wood at age 13 years, whereas it took 1, 2 and even 4 more years for the ‘moderate’, ‘heavy’ and ‘extreme’ variants, respectively (Fig. 3).

Altogether, these results suggest that thinning had a postponement effect on producing mature wood. However, a clear effect was observed only in the ‘extreme’ variant. Koubaa et al. (2005) also reported that silvicultural practices can influence the transition age from juvenile to mature wood.

Tasissa and Burkhart (1998b) and Alteyrac et al. (2006) studied the influences of thinning on the transition age from juvenile to mature wood in loblolly pine grown in the USA. The authors concluded that there were no consistent trends relating thinning to the transition age of juvenile–mature wood, which differ from the findings of this study. Clear trends in the cited studies might also not have been observed as extreme thinning was lacking, comparable to the case in this analysis.

Finally, it could be stated that trees started producing mature wood

- at age 13 years in the ‘without’, ‘moderate’ and ‘heavy’ variants and
- at age 17 years in the ‘extreme’ one.

The difference between juvenile and mature wood densities within the thinning variants substantiated the segregation between both (Table 5). The density of juvenile wood was substantially lower (around 20%) compared to mature wood.

However, no differences were detected of the same wood type between thinning variants, suggesting that similar wood was produced despite starting at different ages.

Considering the above-cited transition ages, the diameter of the juvenile wood was widest in the ‘extreme’ variant, but similar among trees of the other treatments (Table 6). Regarding the proportion of juvenile wood in relation to tree diameter, it was verified that the ‘moderate’ regime was optimal for restricting the size of the juvenile core. The ‘heavy’ variant showed a juvenile core similar to the ‘moderate’ one, but as large as those observed in the ‘extreme’ and ‘without’ treatments.

Zobel and Sprague (1998) also concluded that widely planted loblolly pines resulted in larger juvenile cores. However, the juvenile cores were proportionally smaller compared to the total tree volume in comparison with the values obtained in this study.

Results found by Harding (1990) indicated that volumes of mature wood are approximately the same in widely and closely spaced plantations, and therefore, the size advantage in the widely spaced trees consists primarily of juvenile wood, which is in line with the results obtained in the ‘extreme’ variant.

It is important to note that the lower proportion of juvenile wood obtained in moderately thinned stands might not be true for harvesting trees at earlier ages (Gapare et al. 2006), as can be supposed by the lower wood densities obtained by trees at ages earlier than 20 years (Table 7).

Results from this study indicate that, regardless of some differences among thinning variants, the proportion of juvenile wood was remarkably high, ranging from 61 to 77%, even for an unusually long production period (30 years) for Brazilian standards in managing loblolly pine stands. If the management goal is to produce high-quality timber and the amount of juvenile wood needs to be restricted, the main factor is to lengthen the production period.

Senft et al. (1985) found a juvenile wood core proportion of 31–55% of loblolly pine trees with 30 years of age, when tree diameters ranged from 24 to 31 cm. According to the authors, if strength of wood is required, the harvest age must be postponed until mature wood proportion has increased.

Regarding the same harvest age while comparing the mean wood densities obtained from different thinning variants, no differences could be detected among treatments (Table 7). This means that at the same harvest age, thinning had no effect on mean wood density. However, within a single thinning variant, harvest age was a determinant for producing higher-density wood. In general, it could be observed that the same average wood density obtained at 30 years of age was already reached at age 20 years for all treatments.

Conclusion

The following main results were obtained:

- The maximum ring width was similar among thinning variants (~ 22 mm), being restricted to the core of the trees. Ring width during the mature wood formation was similar among thinned variants (4–5 mm). Although rings were smaller in

the stands without thinning, all studied variants delivered mature timber suitable for high-valuable-appearance end-uses.

- Ring density exhibited a consistent general pattern of increasing values with age, regardless of thinning intensity. No influence of thinning on the wood density was detected when averaged for the entire radial segments. Instead, thinning caused a more homogenous density profile.
- The transition from juvenile to mature wood occurred between ages 13–17 years. Extreme and early thinning delayed the production of mature wood by ~ 4 years compared to no thinnings or practice-oriented ones.
- The diameters of the juvenile wood core were similar between practice-oriented crown thinning regimes and non-thinned ones, but they were greater under the ‘extreme’ thinning intensities. Trees in practice-oriented thinned stands produced a greater radial segment of mature wood than non-thinned stands. Although ‘extreme’ thinning resulted in similar radial segments of mature wood as observed in non-thinned stands, it was formed after a greater juvenile core; thus, the volume of mature wood produced in the ‘extreme’ variant was obviously greater. To obtain an optimal proportion of juvenile/mature wood, extreme thinning within the first ~ 13 years should be avoided. Afterwards, thinning can be intensified.
- At the same harvest age, thinning had no effect on wood density. However, harvest age itself was a determinant for obtaining wood of higher density. The same mean wood density produced at age 30 years could be obtained at age 20 years in all studied variants, but not in shorter production cycles.

Altogether, the results indicated that, from a practical perspective, there are no constraints related to wood ring width and wood density by applying crown thinning to loblolly pine stands in southern Brazil. Even extreme regimes could be of some interest, provided production cycle is long enough to produce mature timber.

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