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ORIGINAL PAPER

Recovery rate and quality of rotary peeled veneer from 30-year-old *Pinus taeda* L. logs

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Abstract

· ***Context*** In the construction sector, wood is facing competition with other materials such as concrete, steel or plastics. Therefore, there is a need for more efficiency in the forest–wood chain by improving silvicutural management and wood processing technologies.

· ***Aims*** The objective of the study is to analyse the influence of log diameter and quality to recovery rate, veneer quality and economic benefit.

· ***Methods*** The trees used in the study came from a 30-year-old *Pinus taeda* L. thinning trial in Southern Brazil. In total, 57 logs (20.7 to 67.0 cm) were peeled following the standard industrial processing methods of the plywood mill.

· ***Results*** Average recovery rate was 54 % ranging from 35 to 72.6 %, with a linear trend (R^2=0.48) of increasing recovery with an increment on the log small-end diameter. Results show that the gap between theoretically possible and real recovery was lower in the logs with bigger diameters, indicating their higher efficiency in industrial processing. Moreover, the economic analysis detected that the current prices for log assortments reflect only the industrial potential of low-quality pruned logs. An optimised pruning strategy would result in higher industrial efficiency, which would allow higher log prices.

· ***Conclusion*** The results indicate that the recovery rate of bigger logs is higher in terms of volume of peeled veneer. The quality and therefore the value obtained from each log were negatively influenced by inadequate pruning strategies. Management of pines for higher value utilisation requires optimized thinning and pruning strategies in order to meet high growth rates and proportionally bigger dimensions of clear wood.

Keywords Softwood · Thinning · Pruning · Higher value utilisation

1 Introduction

In 2011, planted forests covered 7 million ha in Brazil, of which 25.2 % were pine plantations (ABRAF 2012). According to the same source, the domestic roundwood consumption in 2011 was 170 million m^3; solid wood industry accounted for 32 million m^3, 85 % provided by the genus *Pinus*. In the same year, plywood producers consumed 3.7 % of the whole domestic roundwood production, which placed the country in eighth position worldwide, providing 6.2 % of the plywood volume sold on global market.

In the last 12 years, the Brazilian plywood sector grew with an annual rate of 2.3 %. Nevertheless, the sector passed through difficulties in the last years, chiefly increases in internal production costs associated with currency fluctuations—the main reason for the segment's loss of international competitiveness. Losses of export markets, mainly in 2009, were compensated by an increase in domestic demand (ABRAF 2012). The problems faced in 2009 led to innovation processes such as minimising waste of raw material and improving the efficiency of the rotary peeling process.

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Contribution of the co-authors Leif NUTTO strongly participated in the data analysis and the approach which was applied, contributing essentially to introduction, results and discussion.
Antonio R. HIGA supported the design of data collection and the beginning of the data analysis, as well as read the final version of this paper, made corrections and further suggestions.

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Veneer products, such as plywood and laminated veneers, have been developed as an alternative to solid products (Tenorio et al. 2011) and are increasingly used in applications typically dominated by steel and concrete (Lam 2001). Veneer products are also lightweight, relatively rigid and dimensionally stable in comparison to the solid wood ones. Other important advantage of these products is their ecological benefit, namely their positive environmental impact during raw material production and low energy consumption needed in their transformation, besides the biodegradability of the final products (Ozarska 1999).

Today, as the demand for saw and veneer logs is getting stronger and raw material costs are rising, constituting an increasingly higher percentage of the total costs for mills, it has become even more important for lumber and plywood mills to focus on value recovery and quality of products rather than just outgoing volumes. In the plywood sector, manufacturing advances include the use of power drive rolls to decrease spinout, the advent of better lathe technology (which can minimise peeler core diameter) and the use of laser enhanced clipping to aid in the recovery of valuable veneer (Vlosky and Panwar 2012).

Due to the global shortage of large diameter logs, industries have to process lower quality logs and less promising species. To avoid substitution effects by more competitive materials like plastic packaging or Oriented Strand Board panels, innovative processes should take place in the rotary peeling industry to improve the productivity, the yield and the quality of veneers in order to remain competitive at an international level (Denaud et al. 2007, 2012).

Brazilian pine plantations have been managed on relatively short rotation cycles of 15–20 years for the production of pulpwood and small- or medium-sized sawlogs. Although loblolly pine (*Pinus taeda* L.) is the most planted conifer in Brazil, little is known about the tree's characteristics, growth performance and industrial yield of logs from older plantations, aiming for bigger-sized logs for high-quality veneer or timber production.

The strategy of producing high-quality logs could be interesting for both wood producer and the wood industry (Carino and Biblis 2000; Cown 2005) since variations in the wood characteristics of *P. taeda* have direct impact on its economic value (Siqueira 2004).

Therefore, silvicultural regimes aiming to achieve a wood quality suitable for multiple uses could be an interesting option. However, it is important to consider the economic viability of longer rotations, which are strongly correlated with the industrial potential of the logs produced under such growth conditions. A study conducted by Biblis (1996) confirmed that the mechanical properties of LVL fabricated from 20-year-old plantations are significantly lower than corresponding properties of the same product made with veneers of logs from older natural stands.

Of particular importance for recovery rate and quality of peeled veneer are two main factors: log diameter and internal knottiness, as the grading rules existing worldwide confirm. It is noteworthy that the relationship between wood quality and silviculture is quite complex (Zobel 1992). Methods that predict veneer yields obtained from trees and tree components are an essential part of such an assessment (Lynch and Clutter 1998).

However, reliable data about pines used for higher value utilisations from fast growing plantation managed specifically for this purpose are still missing in Brazil. Plywood industry is highly interested in having high-quality logs of bigger dimensions because of expected economic benefits. On the other hand, tree growers are carefully looking after fast return on investment, which is influencing rotation cycles significantly and also the decision whether the logs are pruned or not.

In this context, the overall objective of the study is to analyse the recovery rate and veneer quality of logs of 30-year-old plantation grown *P. taeda* in Southern Brazil, which were derived from a thinning trial. Analyses were carried out by monitoring a standard industrial process. The specific objectives are to (1) evaluate recovery rate and quality of rotary peeled veneer produced from logs of different dimensions, (2) model possible interactions between log parameters and veneer yield and quality, including pruning, and (3) conduct an economic analysis of the results.

2 Material and methods

The logs analysed in this study were harvested in a 30-year-old experimental thinning trial, belonging to a privately owned forest enterprise located in the state of Santa Catarina, Southern Brazil. The experiment was conducted in 1986, selecting a 5-year-old loblolly pine plantation for a thinning trial. It was designed to have a gradient of different thinning intensities. The differences in thinning were determined by the number of competitors taken per potential future crop tree (none, one, two and all). Later, the number of future crop trees was also reduced in different intensities. All the trees were pruned up to 2.5 m in height in year 5. A second pruning procedure took place 2 years later, when only the best 400 trees/ha ('potential crop tree candidates') were pruned up to a height of 6.5 m.

From 24 trees, a total of 57 green logs with a length of 2.40 m were cut and transported to a medium-sized plywood mill. The mean conversion ratio of ton per cubic metres for the transported logs was 1.068. All logs from the experimental trial were peeled, even the ones with a small end diameter less than 25 cm, which generally are not used in the South Brazilian plywood industry. Logs were not debarked before peeling, all diameter values were measured over bark.

Out of the 57 logs, 24 were pruned (second log) and 33 of them, classified as third to ninth log within a tree, did not have any pruning treatment (Table 1). The bottom logs did not enter in the peeling experiment since they were used for producing higher value sliced veneer. Average log diameter and log length were used for volume calculation for the peeling process.

For economic evaluation, assortments were classified by small-end diameter and its respective price, according to the values of the forest enterprise (Florestal Gateados, personal communications, 2011), which are representative of the regional market: '18 to 24.9', '25 to 34.9' and '>35 cm', with values of 29.30, 40.00 and 54.90 US$ per ton, respectively, for unpruned logs. The pruned assortments were split into two groups: '25 to 39.9' and '>40 cm', with values of 54.60 and 89.60 US$ per metric ton.

Since diameter classes for log prices are not uniform and vary widely, for modelling purposes more narrow and constant classes of only 5 cm width were considered as more efficient (Table 1). The assortment named '>50 cm', for pruned logs, was composed of logs with a maximum diameter of 67 cm at small end. Similarly, for the unpruned '>50 cm' assortment, the largest small-end diameter reached 56.5 cm.

Previous to the peeling process, logs were covered with a tarpaulin and steamed for 15 h at a temperature higher than 60 °C. For the rotary peeling process, a 2.800×100-mm rotary lathe (log length×minimum core), manufactured by 'Henrique Benecke Máquinas Industriais', with a fixed knife parallel to the central axis of the logs, was used. Perpendicular knives to the lathe reduced veneer length to 2.30 m. In general, after the peeling process, a standard core of 10 cm of diameter remains. However, since the normal industrial process was used, some cores of poorer quality (excessive knots) were left in bigger dimensions by the operators, influencing the comparability of the results for recovery rate.

Table 1 Assortments by diameter classes and pruning, number of logs, log number within a tree, average volume (V_{log}) and commercial price per log

Diameter class (cm)	Number of logs	Log number	V_{log} (m³)	Value (US$/log)
Pruned				
20–24.9	1	2	0.081	6.30
25–29.9	2	2	0.128	14.20
30–34.9	3	2	0.208	24.20
35–39.9	1	2	0.287	33.20
40–44.9	3	2	0.336	64.20
45–49.9	7	2	0.406	77.10
>50	7	2	0.518	118.30
Unpruned				
20–24.9	1	9	0.109	7.40
25–29.9	8	6–9	0.145	13.00
30–34.9	7	3–8	0.187	16.80
35–39.9	7	3–7	0.267	32.10
40–44.9	6	3–7	0.326	39.30
45–49.9	2	4–5	0.434	54.10
>50	2	3–4	0.566	63.20

Limits in fixing the big-sized logs were observed, due to the technical limitations of the used equipment. The forces acting in the peeling process of bigger logs are much higher at the beginning of the peeling than in smaller logs. The two clamps of the chuck which fixed the log were not designed for peeling logs of bigger dimensions. Those of the machine used in the experiment only grabbed in the juvenile core zone of the pith, causing a slipping of the logs. Even the rotary lathe machine used represents a high standard in the Brazilian plywood industry; it was not fully adapted to the conditions of the experiment, specifically for the logs bigger than 45 cm.

Veneer was peeled into 3-mm sheets, being linked to the log from which it originated. Furthermore, veneers were visually graded by the operator just before cutting in the respective dimensions (Table 2). Grading rules followed the national standards (ABIMCI 2002) where veneers classified as 'A' are the most valuable, clear of knots and other imperfections. Class 'B' have some defects—e.g. till ten green knots per sheet with less than 10 mm of diameter—and class 'C' with no limits related to knots. Veneer class named 'R' has the same thickness and length as the other sheets, but is of a smaller width. Therefore, class 'R' are only used to fill internal layers of lower quality plywood.

Commercial values correspond to the average market prices in the region of Lages, SC, Brazil, sold by the rotary peeling veneer industry. Cores as well as other by-products were not considered.

Length, width and thickness of veneers were taken as constant for the recovery analysis. Theoretical recovery, as the maximum recovery rate to be obtained for a log, was determined by the difference between the volume of the log small-end diameter under bark and a residual core 10 cm of width (Lynch and Clutter 1998).

Table 2 Dimensions, volume and commercial value of the produced veneer sheets; thickness (3 mm) and length (2.30 m) are kept constant in the production process

Products	Width (mm)	Volume (m³)	Value (US$/m³)
R	280	0.002	48.30
A	1,240	0.009	314.00
B	1,240	0.009	229.50
C	1,800	0.012	169.10

From the difference between individual log prices, and the gross revenue obtained by them, it was possible to determine the economic benefit depending on the log assortment (diameter and pruning). Other costs related to the industrial process were not considered in this study.

Statistical analyses were done considering a fully randomised sampling design. Standard regression techniques were used. According to the objectives of the study, in a first step only recovery rate was analysed to develop linear models for predicting veneer yield depending on log dimension. The variables used for modelling were tested in a correlation analysis and then included in the regression analysis (stepwise forward method). Only terms with significant *F* values (≤0.05) were employed. The coefficients of determination (R^2), standard error of the estimate variable and graphic residuals analysis were used as criteria for selecting the best fitted models.

3 Results

The correlation analysis after Pearson showed that 'small-end diameter' (SED) was the variable with highest correlation coefficient with log relative recovery (0.695). In fact, all of them were significantly correlated with the target variable, except log taper (Table 3).

As expected, log number within the tree and relative knotty core zone were negatively correlated to the recovery rate. Although mean log taper was 1.2 cm per 1.0 m of log length, it varied from 1.6 cmm^{-1} for the logs localised between 2.40 and 4.80 m of the tree height (second log), and 0.9 cmm^{-1} for the logs of higher sections. The largest analysed log, with a small-end diameter of 67 cm, had a taper of 4.6 cmm^{-1}, which explains, at least partially, the low recovery rate observed in this sample. The fact that the variable is not correlated significantly to recovery rate in this study might be due to the large number of logs with low taper. For a stratification of the logs after height of the log section in this study, the number of observations in each class was too low for statistically representative results.

The stepwise regression procedure for modelling recovery rate selected 'SED' and 'V_{total}' as the two most significant variables (Table 4). 'SED' explained 48 % of the occurring variance, while 'V_{total}' contributed another 5.5 %, reducing the standard error of the model from 6.6 to 6.2. However, the variance inflation factor was equal to 24.4, indicating a high multicollinearity between both variables. Because of marginal contribution of the 'V_{total}' variable to the recovery estimation, only 'SED' was employed on the final equation, utilized in the further analysis. A second reason for omitting 'V_{total}' is the problem of multicollinearity between both variables. Although adding variables such as 'Kontzone' and '$\mathrm{Log}_{\mathrm{number}}$' to the model could be of practical relevance, it showed no improvement to the estimation quality and therefore were not considered (Table 4).

Predicted recovery rate obtained throughout Eq. 1 compared to real recovery rate is shown in Fig. 1.

$$\text{Recovery rate} = 30.403 + 0.602\ (\text{SED}) \tag{1}$$

Residual analysis of the recovery model indicated unbiased prediction. However, it is important to note that the fitted equation is only valid if the independent variable is kept within the ranges of the data used for estimating the model parameters.

Results showed that average recovery was 54.2 %, ranging from 35 to 72.6 %, with a linear trend of increasing recovery with an increment on the log SED. Although the linear trend has shown a relatively weak coefficient of determination (R^2=0.48), the equation (Eq. 1) means that the veneer recovery increases at a rate of 0.6 % per unit increase in the value of log diameter.

Logs of the diameter class '20–24.9' were not analysed due to the small number of logs (two) in this class.

Table 3 Pearson coefficient of correlation and probability between analysed variables

Variables	Recovery	LED	AD	SED	V_{total}	V_{cylinder}	Knotzone	$\mathrm{Log}_{\mathrm{taper}}$	$\mathrm{Log}_{\mathrm{number}}$
Recovery	1								
LED	0.656***	1							
AD	0.677***	0.997***	1						
SED	0.695***	0.986***	0.996***	1					
V_{total}	0.630***	0.990***	0.988***	0.979***	1				
V_{cylinder}	0.651***	0.985***	0.991***	0.989***	0.996***	1			
Knotzone	−0.325***	−0.550***	−0.544***	−0.535***	−0.546***	−0.542***	1		
$\mathrm{Log}_{\mathrm{taper}}$	0.077***	0.503***	0.433***	0.354***	0.483***	0.404***	−0.315***	1	
$\mathrm{Log}_{\mathrm{position}}$	−0.349***	−0.524***	−0.535***	−0.542***	−0.517***	−0.526***	0.591***	−0.135	1

LED large-end diameter, *AD* average diameter, *SED* small-end diameter, V_{total} log total volume, $V_{cylinder}$ log volume obtained by small-end-diameter, *Knotzone* relative knotty core zone, Log_{taper} reduction in diameter (centimetres) per length (metre), Log_{number} between second and ninth

*$p<0.10$; **$p<0.05$; ***$p<0.01$

Table 4 Summary of the different models for predicting recovery rate, considering influencing variables

Model	Lower	β0	Upper	Lower	β1	Upper	Lower	β2	Upper	R^2	Syx
1 (SED)	23.5	30.403	37.3	0.4	0.602	0.8				0.48	6.56
2 (SED, V_{total})	−6.8	9.667	26.1	0.9	1.657	2.4	−107.2	−61.968	−16.7	0.55	6.20
3 (SED, Knotzone)	14.2	27.277	40.4	0.4	0.633	0.8	−5.9	2.313	10.5	0.49	6.60
4 (SED, $Log_{position}$)	18.4	29.035	39.7	0.4	0.621	0.8	−0.8	0.157	1.1	0.48	6.61

β_i parameters values, lower and upper bounds of the 95 % individual prediction interval (CLI), R^2 coefficient of determination, S_{yx} standard error of the estimate

Significant differences were detected for the recovery rate ($F_{(49,54)}=10.496$; $p<0.01$) among assortments. In the class of '35–39.9' cm, the recovery rate resulted in statistically similar values compared to the logs bigger than 50 cm. Theoretical recovery was calculated for each assortment, and the difference between the latter and the real one (Δ) was obtained in order to evaluate assortment recovery efficiency (Table 5).

The veneer grading analysis showed an expected result because pruned logs with small-end diameter bigger than 35 cm produced higher rates of sheets graded as 'A' (Fig. 2).

An economic analysis was done in order to understand fully the pruning consequences in the veneer grading, as well as veneer recovery rate (Fig. 3). Costs, as well as revenue per log, showed an exponential trend. For pruned logs, the quotient between (revenue−cost)÷cost increased with bigger diameters. The difference for the material used in the study was not that obvious because of big size of the knotty zone.

Logs with knotty core zones of less than 39 % of the small-end diameter (five logs) were utilised for simulating a maximum revenue model, while the other trees (13 logs) with knotty cores ranging from 44 to 88 % of diameter were used for showing the minimum trend.

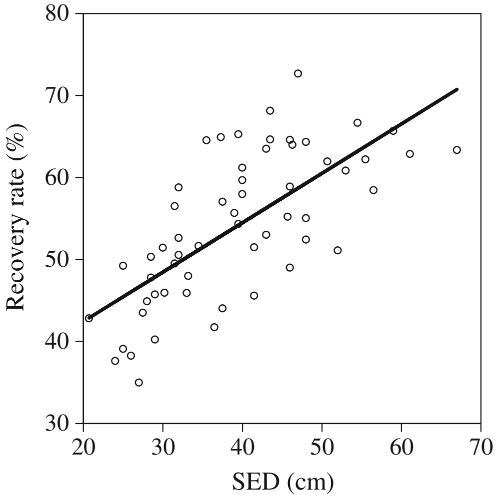

Fig. 1 Observed recovery rate of produced veneer (*circles*; in percentage) and predicted line (Eq. 1) with help of log small-end diameter (SED)

The maximum and minimum trends as absolute values are presented as relative numbers (Figs. 3 and 4). Maximum and minimum trend lines proved that logs with knotty core zones bigger than 40 % negatively influenced the potential economic revenue in a significant way.

Trends shown in Fig. 4 are explained by the equations below, for pruned (2, 3, 4 and 5) and unpruned logs (6 and 7):

$$Max.\ value = 195.562(SED)^{1.133} \quad R^2 = 0.979 \tag{2}$$

$$Min.\ value = 141.995(SED)^{1.058} \quad R^2\, 0.841 \tag{3}$$

$$Revenue = 0.0007(SED)^{2.928} \quad R^2 = 0.925 \tag{4}$$

$$Cost = 0.0008(SED)^{2.777} \quad R^2 = 0.980 \tag{5}$$

$$Revenue = 0.0017(SED)^{2.627} \quad R^2 = 0.913 \tag{6}$$

$$Cost = 0.923(SED) - 19.656 \quad R^2 = 0.979 \tag{7}$$

The knotty core zone in percent for each analysed log (Fig. 5) allows a better understanding of the reasons which

Table 5 Real and theoretical mean recoveries of the assortments with the differences between both (Δ)

Assortments (cm)	Real recovery (%)	Theoretical recovery (%)	Δ
20–24.9	–	–	–
25–29.9	43.4 c	71.7	28.3
30–34.9	51.1 bc	74.6	23.5
35–39.9	55.9 ab	78.2	22.3
40–44.9	58.3 ab	79.9	21.6
45–49.9	59.6 ab	79.0	19.4
>50	61.4 a	79.5	18.1

Real recovery (percentage) with the same letter is not significantly different at an alpha level=0.05 (test of Tukey). Class variable: assortments

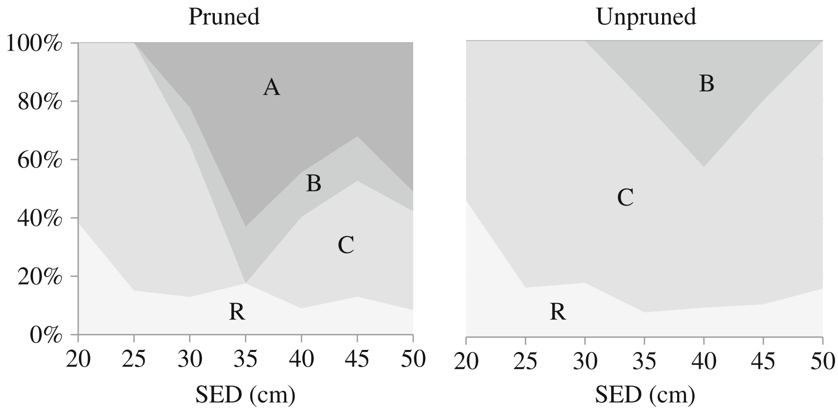

Fig. 2 Veneer grade (in percentage) depending on small-end diameter of pruned and unpruned logs. Grading: *A*=clear; *B*=till 10 green knots per sheet (Ø<10 mm); *C*=no limits; *R*=sheets with only 280 mm width

led to the unexpected low economic benefits for the pruned and big-sized logs. As the log with knotty core less than 40 % was highlighted, it is clear that the majority of the pruned analysed logs had a knotty core higher than 50 %. Surprisingly, some of the pruned logs had a knotty (or other defects) core of about 100 % of the log small-end diameter.

4 Discussion

SED alone composed the recovery rate model with a coefficient of determination that shows a good predictability of the model (R^2=0.483; S_{yx}=6.559).

Similar to this study, results obtained by Kewilaa (2011) revealed that 73.6 % of the variation in veneer recoveries variable is explained by log diameter. The log ovality could be another factor (Bonduelle et al. 2006). The same authors report a loss of 35 % in volume during the rounding process, as far as the whole length of the log is being peeled, although log taper showed a higher correlation with veneer recovery (0.27) than it was observed in this study. Moreover, high taper in logs from trees contributes to lower recovery because more of the block volume is outside the peelable cylinder and cannot be used for veneer production (Fahey et al. 1991).

Although the bark width was not specifically considered in this study, it might have an impact to recovery rate too. Bortoletto Jr. (2008) reported a loss of 13.5 % only due to this variable.

Olufemi (2012) analysed the recovery rate of *Brachystegia nigerica* logs with small-end diameter of about 60 cm. The author found yields for peeled veneers ranging from 14 to 46 %, significantly depending on steam temperature and duration, which resulted in varying core diameter dropout. Although the species studied in this trial cannot be related to the one mentioned above, the result obtained by Olufemi (2012) might be an indicator that bigger-sized logs could not have been efficiently steamed in this study, compared to the smaller ones, resulting in an additional source for the variation in recovery rate. According to Aydin et al. (2006), heating of logs with steam is one of the most important processes during the veneer manufacturing. The main function of steam heating is to soften veneer log temporarily and make it more plastic, pliable, more readily peeled, and improving the quality and quantity of material recovered from the log.

The average recovery rate was 54 % showing high variation around this value. Although a numeric and linear increasing trend could be shown, logs with diameters bigger than 50 cm had a recovery rate similar to the assortment of '35–39.9' cm. Pruned logs with small-end diameter bigger than 35 cm resulted in higher rates of grade 'A' sheets. This trend was not so evident due to the high proportion of knot

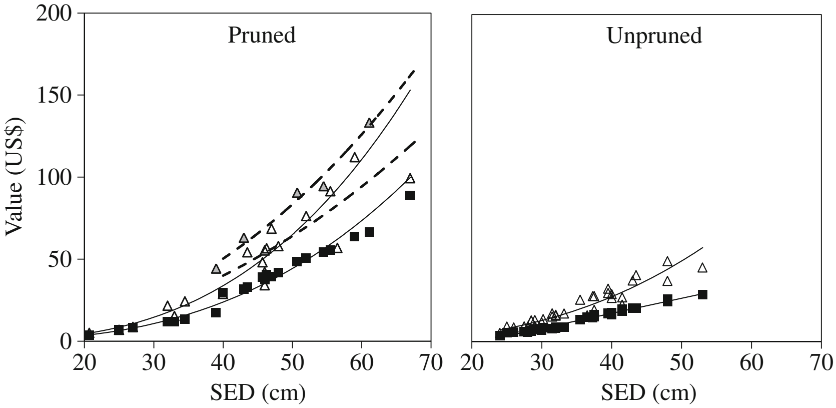

Fig. 3 Costs (*square*), gross revenue (*triangle*) for the pruned and unpruned log assortments depending on small-end diameter (SED); Power trends for data (*full line*); maximum (*max.*) and minimum (*min.*) trends depending on knotty core ratio; pruned logs with knotty core zone less than 39 %, relative to SED are highlighted as *grey triangles*

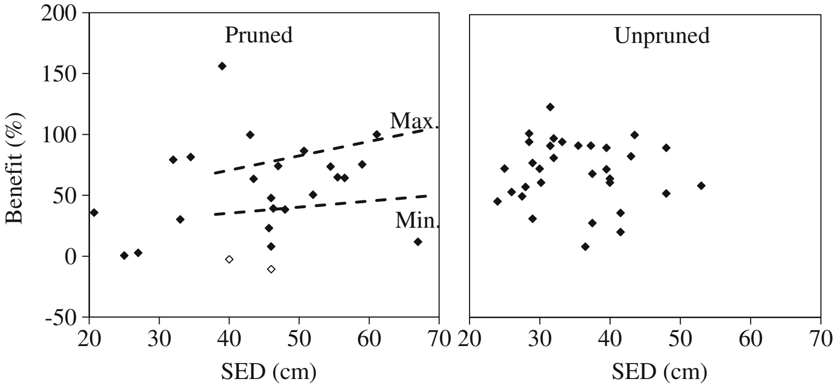

Fig. 4 Economic benefit (in percentage) of pruned and unpruned logs depending on small-end log diameter (SED); maximum and minimum trend lines, depending on knotty core ratio, less than 39 and between 44 and 88 %, respectively (*dashed lines*). *Unfilled diamonds* highlight negative values

zone (knotty cylinder in relation to log small-end diameter), especially in the bigger-sized logs.

Similar to this study, Wang and Dai (2008) report a veneer recovery of 50.6 %. Fahey et al. (1991) found an average recovery rate just under 60 % for logs with about 40 cm of diameter, while Vilela et al. (2012) reported an average recovery of 64.5 %, obtained with logs varying from 25 to 40 cm in diameter. Brand et al. (2004) obtained only 46.5 %.

After Lynch and Clutter (1998), an average theoretical recovery of 76.5 % was calculated for all the studied assortments. The theoretical recovery rate calculated for each diameter class grew with the increase of the log small-end diameter, but the real recovery grew even more sharply, resulting in a reduction on the difference between both (Table 5).

In a study conducted by Cardoso (2009), only 21 % of the theoretical recovery rate of pine logs was reached, which corresponded for 10.8 % of the total log volume, ranging from 1.2 to 17.7 %. According to the author, only 1/3 of the logs used in the study were pruned.

A frequently used terminology in the Brazilian wood industry is the quantity of logs in tons, needed for the production of one cubic metre of final product, called ‘conversion factor’. This measure was obtained with the inversion of the recovery rate, which varied from 2.34 to 1.64, for the assortments ‘25–29.9’ and ‘>50’, respectively. The Brazilian plywood industry reports an expectation of no less than 2:1, which means that 2 m^3 of roundwood is necessary for the production of 1 m^3 of peeled veneer.

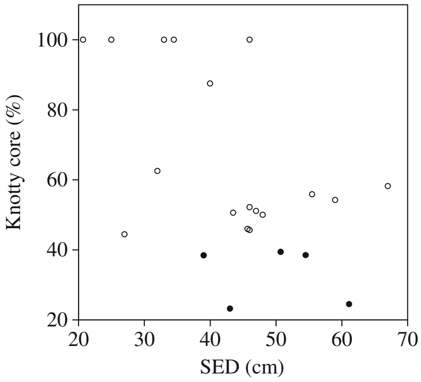

Fig. 5 Knotty core zone (percentage) depending on small-end diameter (SED); logs with knotty core less than 40 % are highlighted (*black*)

The trend of producing higher rates of sheets graded as ‘A’ was not so evident due to the low quality of pruning, especially in the bigger-sized logs (Fig. 2). Because the origin of the logs was a thinning trial, the bigger-sized logs were obtained in extremely intense thinning regimes, with high growth rates starting from year 5. The second pruning lift (2.5 to 6.5 m) was only carried out at year 7, when the stems already showed more than 30 cm of diameter at the second log basis, resulting in a knotty core of big dimension. Furthermore, it is important to note that this experiment started at the beginning of pruning and thinning treatments on *Pinus* stands in Southern Brazil. This fact might explain the low efficiency of the pruning due to untrained forest workers, leaving behind small branch stubs or hitting the branch collars, leading to extended periods of cicatrisation.

Veneer sheets graded as ‘C’ increased in logs above 40 cm in diameter because the strong thinning intensities and, consequently, larger knots resulted in a lower veneer quality. This grade of peeled veneer is generally used for internal layers of the plywood, while grade ‘B’ and preferably ‘A’ perform the external ones. Although the quantity of internal sheets is higher than the external ones, the production of class ‘C’ is frequently higher than the demand.

Rate of class ‘R’ veneers decreased with increasing small-end diameter for both pruned and unpruned logs. It is important to note that the residues in this case were veneer sheets of comparable thickness and length of the normal products; the only difference was the standard width of 280 mm (Table 2).

The effect of pruning in veneer grading is obvious in terms of sheet quality (clearwood), but not so obvious in the amount of veneer produced (cubic metres or percentage). This is because in the general industrial processing procedure, logs with too many knots were not fully peeled, resulting in bigger unpeeled cores, thus influencing negatively the recovery rate.

The knotty core zone of 39 % (about 1/3) was taken for the economic analysis following the study of Schulz (1959), and confirmed by Seitz (2000), who indicated a maximum knotty core of one third of the diameter as economically acceptable. The "one third" rule might be of less importance for logs of bigger dimensions, although it is a minimum condition for logs between 30 and 45 cm. Noteworthy is that, from the economic point of view, pruning is an investment which should always aim for the optimisation of the return of investment. In this respect, it cannot be justified to make a late pruning only because the bigger target diameter still allows having an acceptable recovery of clear wood while processing.

It was found that the best economic results were not obtained from the bigger-sized pruned logs. Seitz (2004) took the market prices of the bigger dimensioned pine logs for a detailed economic analysis, concluding that the higher costs per volume are compensated by higher recovery rates. This conclusion might be valid if pruning is conducted in the way suggested by him (Seitz 2000). In the present study, this was not the case, where the percentage of the knotty core zone is exceeding the expectations (Fig. 5). Since bigger-sized logs are more expensive than small ones, the same level of benefit rate does not mean the same absolute revenue, but the same proportion in relation to log price.

Even for the best five pruned logs, with knotty core less than 40 % (Fig. 5, highlighted circles), the economic benefit remains on the same level as observed for the unpruned logs (Fig. 4). Throughout this analysis, it can be concluded that the higher prices charged for the pruned logs (pruning premium) are already compensating the potential of producing higher graded veneer, as compared to the unpruned ones. If this potential is compromised by low efficient pruning methods, plywood industry cannot afford to pay higher prices for such logs. On the other hand, when pruning is carried out in order to restrict the knotty core zone to 30 % of the log small-end diameter, industry can afford higher prices, which benefit the whole production chain.

The two negative values shown in Fig. 4 indicate that the price for a poorly pruned log is higher than the revenue that can be achieved from the peeled veneer. The economic loss would be even higher if all the costs involved in the industrial process were considered. According to Polzl (2002), log prices are only 50 % of the total costs in the plywood industry.

A study conducted by Fahey and Willits (1991) shows that logs with less than 30 cm of diameter should not be peeled. The results in Table 2 confirm the low recovery rate of these assortments. However, this could not be confirmed by the economic analysis (Figs. 3 and 4), where both pruned and unpruned logs resulted in similar levels of economic benefit, although a slightly increasing trend could be noted for the pruned logs.

The material used for this study could only partially reflect the potential of pruned logs of bigger diameters coming from fast growing plantations. Therefore, it can be concluded that the higher prices charged for the pruned logs already compensate its industrial potential to produce higher grade veneers, which can be sharply compromised by low efficient pruning methods, especially when the log is not fully peeled.

Even so, by taking off the defects in a simulation, the economic potentials of bigger dimensioned pines with adequate pruning could at least be partially assessed (Figs. 3 and 4, upper dashed lines). Since the best quality bottom logs were not included in the study, the economic outputs cannot be fully evaluated and might be better than estimated in this analysis.

The management applied in the experiment did not lead to satisfactory results in terms of knotty core of the logs. Pruning activities should be focused on the final utilisation of the log, leading to a knotty core of a dimension not influencing negatively economic results. From a silvicultural point of view, considering growth conditions of *P. taeda* in Brazil, it is possible to restrict the knotty core to a radius of 6 cm around the pith, maintaining a satisfactory tree development (Seitz 2000). This value matches with the minimum unpeeled core left in the modern rotary peeling process. The best pruning regime was described by Seitz (2000) as being yearly from the third to seventh year, lifting 1 to 1.5 m each year. Starting early with artificial pruning is necessary due to the fast growth of the specie in the analysed context. Noteworthy is that the remaining crown should be at least 3–4 m in length to maintain an acceptable rate of tree growth (Seitz 2000). Additionally, it is not possible to wait until tree reaches around 6 m in height to prune a whole 2.5-m segment, approximately the first log, because the segment basis would have reached a diameter greater than the 10–12 cm, with direct influences on the final knotty core zone of the log. However, such pruning regimes have to be regarded as critical from an economic and operational perspective and must be evaluated from case to case.

It can be concluded that silvicultural regimes aiming for bigger-sized pruned logs for higher value utilisation are certainly interesting for rotary peeling industry. Higher recovery rates and improved veneer quality obtained from logs produced under specific management practices most likely result in higher log prices.

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