PRUNING *Araucaria angustifolia* FOR KNOT-FREE TIMBER PRODUCTION

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Resumo

Poda de Araucaria angustifolia para produção de madeira sem nós. Embora *A. angustifolia* não seja importante economicamente no momento, a tendência global de conservação dos recursos naturais por meio do seu uso sustentável, juntamente com os resultados recentes do melhoramento genético da espécie estão apresentando perspectivas promissoras para uma nova onda de plantios. Com o presente estudo, objetivou-se determinar intensidades ótimas de poda a partir da avaliação do crescimento em diâmetro e altura de *A. angustifolia*. A qualidade de poda, em termos de oclusão e dimensão do núcleo defeituoso, foi também investigada. O experimento foi iniciado quando as árvores apresentavam 6 anos de idade conduzindo seis diferentes intensidades de poda, nomeadas em função do número de verticilos remanescentes após a poda (0, 2, 4, 6 e 8), assim como árvores não podadas (U) como testemunhas. A partir dos resultados obtidos no presente estudo, concluiu-se que a intensidade da poda é capaz de influenciar significativamente o crescimento de *A. angustifolia*. O crescimento em diâmetro é mais afetado que o em altura. A poda de *A. angustifolia* para a produção de madeira sem nós precisa ser conduzida de forma a manter 8 verticilos remanescentes após a intervenção para que nenhum efeito negativo no crescimento corrente anual em diâmetro seja observado. Um núcleo defeituoso de 15 cm parece ser um objetivo factível para a espécie considerando a intensidade de poda ótima, que evite perdas de crescimento. Essa conclusão dependente da rápida oclusão dos galhos podados que, por sua vez, são resultado de uma boa qualidade de corte dos galhos.
Palavras-chave: Pinheiro brasileiro; Produção de madeira; Manejo Florestal; Uso múltiplo da madeira.

Abstract

Although *A. angustifolia* is currently economically unimportant, the worldwide trend of conservation through the sustainable use of natural resources together with recent results of genetic breeding are delivering promising perspectives for a new wave of plantations. This study aimed to determine optimal pruning intensity by evaluating the diameter and height growth of *A. angustifolia* trees. Pruning quality in terms of occlusion and defect-core size were also investigated. At the age of 6 years, the pruning experiment was started by conducting six different pruning intensities, named after the number of whorls left after pruning (0, 2, 4, 6, and 8), as well as unpruned (U) trees as a control. From the results obtained in the present study, it was concluded that pruning intensity had a significant effect on the growth of young *A. angustifolia* trees. Diameter was more affected than height growth. Pruning *A. angustifolia* trees for knotty-free timber production must be conducted keeping 8 whorls after the intervention if no negative effect in current annual increment in diameter is to be observed. A defect core of 15 cm seems to be a feasible target for the species regarding optimal pruning intensity to avoid losses in diameter growth. This is strongly dependent on a fast occlusion process, which, in turn, is a result of a careful pruning technique.
Keywords: Brazilian pine; Timber production; Forest Management; Multiple uses of timber.

INTRODUCTION

Araucaria angustifolia (Bertol.) Kuntze, the Brazilian or Paraná pine, is the most important indigenous conifer of Brazil, both ecologically and economically. However, because of governmental regulations, bureaucracy, lack of higher productivity genetic material, and mistakes in the plantations from not knowing the ecology of the species resulted in commercial disinterest (SEITZ, 1986; NUTTO *et al.*, 2005). Currently, there is an estimated area of ~10,000 ha of *A. angustifolia* plantations in the country (IBÁ, 2014; IBÁ, 2017), which is decreasing due to the previously mentioned factors. Nevertheless, following a worldwide trend of conservation through the sustainable use of natural resources, several efforts are in progress. Regulations are under intense discussion, and the results of genetic breeding started in the 1970s by EMBRAPA are now delivering promising perspectives (SOUSA; AGUIAR, 2012; SILVA *et al.*, 2018), which will probably be the genetic base of a new plantation wave.

Additionally, the few commercial plantations of *A. angustifolia* were not always established in proper sites, and were ineffectively managed, providing a perception that does not correspond to the real potential of growth and economic viability of the species.

Even the best sites planted with *A. angustifolia* deliver maximum productivities of 25 m³ ha^{-1} yr^{-1} (NUTTO *et al.*, 2005; DOBNER JR. *et al.*, 2019), half the ones at good sites reported for *Pinus taeda* L., 45-50 m³ ha^{-1} yr^{-1} (ELESBÃO; SCHNEIDER, 2011; DOBNER JR.; QUADROS, 2019), the most cultivated conifer species in the area previously dominated by *Araucaria* forests. Thus, it is evident that *Araucaria* plantations, if commercially regarded, would not have the goal of maximum volume production, but instead, to supply high-quality timber for specific market niches.

In this context, pruning is an important management tool to anticipate and increase the production of knot-free timber. Pruning is the removal of branches from the stem so that knot-free timber is produced. From the silvicultural point of view, it is important to understand the natural pruning behavior of the species, i.e., how long dead branches remain on the stem. *A. angustifolia* has persistent branches, as presented in Fig. 1-a, and must be artificially pruned if knot-free timber is to be produced in commercial rotation lengths. Fig. 1-b was obtained within the experiment presented in this manuscript, at the bottom of one tree. It is the result of forgetting to prune one 'harmless' thin dead branch, as one might suppose by looking at the ones shown in Fig. 1-a.

Figure 1. (a) Persistent dead branches in *Araucaria angustifolia*, resulting in (b) knotty timber.
Figura 1. (a) Ramo morto persistente em *Araucaria angustifolia*, resultando (b) madeira com nó.

The aim of pruning is to keep the defect core as small as possible. This is obtained when pruning is carried out at an early age, preferably by cutting off live branches, so the knot formed until this moment is tight and the occlusion process is faster. On the other hand, by pruning live branches, the photosynthetic area of the tree is reduced, which, in turn, depending on pruning intensity, might reduce growth.

The production of knotty-free timber is achieved by pruning off branches and allowing subsequent diameter growth to first occlude over the branch stubs and then to produce clear wood (MEAD, 2013). The higher the diameter growth of the pruned tree, the more rapid the occlusion process. So, over-pruning trees, with a negative effect on radial growth, is a contradictory consequence of pruning and its goals. Thus, optimal pruning intensities are needed to restrict the defect core to a minimum, while diameter growth is not significantly affected.

With this study, it was aimed to determine optimal pruning strategies by evaluating the diameter and height growth of young *A. angustifolia* trees as affected by different pruning intensities. Pruning quality in terms of occlusion and defect-core size were also investigated. The hypotheses of the study were that pruning of green branches negatively affects tree diameter and height growth; at the same time, green pruning is important to restrict the defect core. Therefore, optimal pruning intensities should be studied. This is an unprecedented contribution since no previous study related to this species could be found.

MATERIAL AND METHODS

Studied stand, treatments, and design

The studied *A. angustifolia* stand was established on an agriculture field due to direct seedling in the municipality of Campo Belo do Sul, Santa Catarina, in southern Brazil (27° 55'33'' S, 50° 50'34'' O, 970 m above sea level).

The region has an average annual precipitation of 1,600-1,900 mm and a mean annual temperature of 12-16 °C (ALVARES *et al.*, 2013). Predominantly, soils are nitosols and cambisols of volcanic origin with basalt and diabase as parental materials (DORTZBACH *et al.*, 2016).

Weed control was conducted during the first three years after seedling.

At the age of 6 years, the pruning experiment was started by conducting six different pruning intensities, as follow:

0 – all whorls were pruned, i.e., no branches were left.
2 – 2 whorls were left after pruning.
4 – 4 whorls were left after pruning.
6 – 6 whorls were left after pruning.
8 – 8 whorls were left after pruning.
U – unpruned trees.

At the age of 7 years, pruning treatments were repeated by removing the additional whorls.

Pruning was conducted with a curved-bladed saw, carefully to avoid stem damages.

The statistical design was fully randomized, where each individual was a replication. Only dominant trees were included in the experiment. Neighbor trees were harvested to capture only the pruning response on an individual free of competition. There were 14 replications per treatment. In total, 84 trees were evaluated.

Field measurements and sampling

The diameter at breast height (*dbh*, 1.3 m), total height (*h*), and the height of the living crown of all trees were measured between 6 (experiment establishment) and 10 years of age with a diametrical tape and a Vertex™ hypsometer, respectively. At the age of 6 years, the mean diameter of trees was 8.8 cm (8.3-9.1 cm), and the mean height was 4.7 m (4.6-4.8 m).

When the stand completed 25 years of age, an exploratory analysis in terms of pruning quality was carried out, in which destructive sampling took place for knotty core and occlusion process evaluations. At this moment, eight trees belonging to the pruning experiment established 19 years ago could be found through preserved markings. Several trees lost their marking, and others have been thinned since the stand followed a commercial thinning schedule after the pruning experiment was terminated.

For this qualitative analysis, eight trees were harvest (d = 26.4 cm, 23-29 cm; h = 16.7 m, 14-18 m) with clear indications of past pruned heights varying between 0.5-4.5 m and thus, regarding all pruning treatments. As a result of the pruned height, between 2-11 cross-sectional discs were sampled exactly at the pruned whorl. At the tree base, since occlusion marks were difficult to detect, cuts were conducted every 3 cm until the whorl and pruning scars were located. With height, whorls were apparent onwards, and cuts were made directly at the whorl marks. As a result, 36 cross-sectional discs were obtained. Discs were dried and sanded. Measurements of the defect core radius at every pruned scar, which, together with the height at which disc was collected, was used to evaluate the defect core cylinder inside the stems.

Data analysis

Quantitative analyses regarded a fully randomized design with a one-way analysis of variance (ANOVA) for the different dendrometric characteristics after evaluating the residuals normality (Shapiro–Wilk) and homogeneity of variances (Bartlett). Once differences between treatments were detected, Tukey's test (α = 0.05) was conducted to segregate treatments.

With the pruning quality analyses, it was aimed to determine the size of the defect-core, which means the knot already formed until pruning plus the occlusion process. This was conducted in an exploratory approach, since only eight individuals could be sampled.

RESULTS

Stand and treatments characterization

At the age of 10 years, dominant height was ~8 m, which indicates an upper-intermediate site quality (site index = 20, index age = 40 years; SCHNEIDER *et al.*, 1992). This is an important consideration for further dendrometric analyses and characterizing the productivity level of the evaluated site.

A descriptive characterization of trees (diameter and height) and pruning intensity (remaining crown in meters and percentage) are given in Fig. 2.

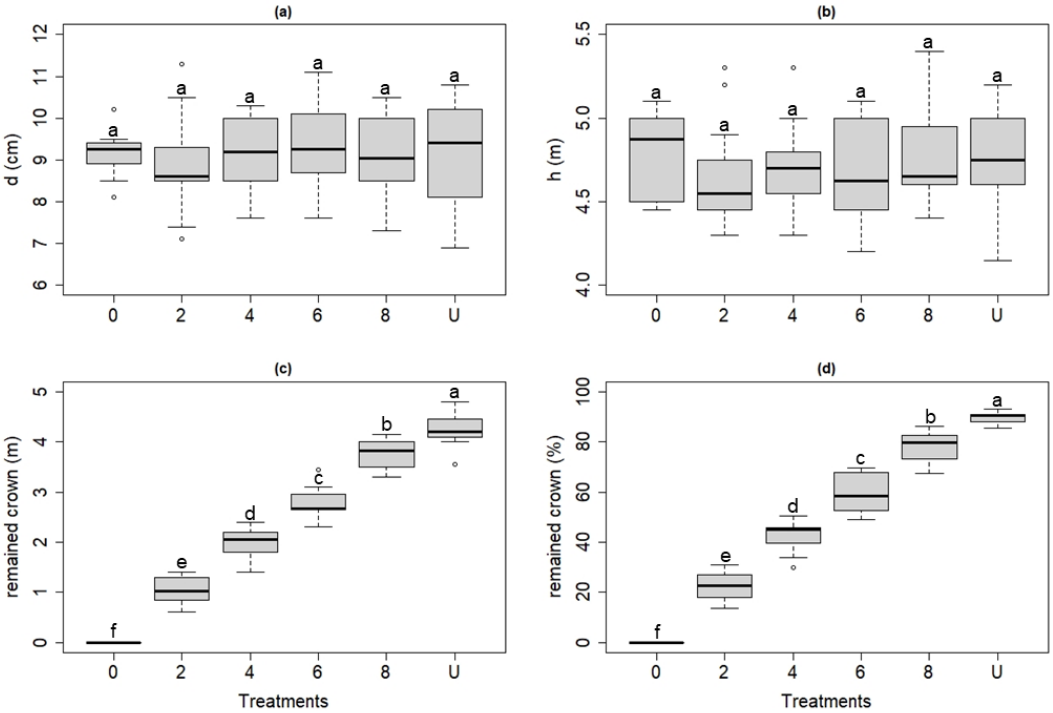

Figure 2. Descriptive statistics of the trees subjected to the different treatments at the age of 6 years: (a) average diameter at breast height; (b) average total height; (c) length of the remaining crown after pruning in meters; (d) remaining crown after pruning in percentage in relation to the total height. Treatments named ‘0’, ‘2’, ‘4’, ‘6’, and ‘8’ indicate the number of whorls left after pruning conducted at the age of 6 years; ‘U’– unpruned as the control. The bold line indicates the median of the data, while the grey box the interquartile range between first (25^{th}) and third (75^{th}) percentiles. Outliers are given as circles. Treatments with the same letter do not significantly differ (Tukey, α = 0.05).

Figura 2. Estatística descritiva para as árvores submetidas aos diferentes tratamentos aos 6 anos de idade: (a) diâmetro à altura do peito médio; (b) altura total média; (c) comprimento da copa remanescente após a poda em metros; (d) copa remanescente após a poda em porcentagem em relação à altura total. Tratamentos nomeados como ‘0’, ‘2’, ‘4’, ‘6’ e ‘8’ indicam o número de verticilos remanescentes após a poda realizada na idade de 6 anos; ‘U’ – não podado. A linha em negrito indica a mediana dos dados, enquanto a caixa cinza a amplitude de variação dos dados entre o primeiro (25) e o terceiro (75) percentis. Dados discrepantes são apresentados como círculos. Tratamentos com a mesma letra não diferem estatisticamente (Tukey, α = 0,05).

From Fig. 2, it can be seen that the diameter (Fig. 2-a) and height (Fig. 2-b) values of the trees subjected to the pruning treatments were similar among treatments at the moment the experiment started (p = 0.94 and p = 0.73, respectively). Thus, implying that differences observed in the further analyses are a result of pruning intensities.

In relation to the pruning intensity, by keeping a certain number of whorls, a gradient of remaining crown was obtained (Fig.2-c), ranging from 0 m for the treatment ‘0’, were ‘0’ whorls were left, i.e., all branches were pruned, to 4.3 m for the unpruned (‘U’) treatment. All treatments differed from each other in terms of remaining crown (p <0.001). It is noteworthy that by only keeping 6 or more whorls, the remaining crown was ≥ 50% in relation to total tree height (Fig. 2-d). As a result of treatment ‘0’, from the 14 replications, four trees died, showing the severity of this treatment.

As a result of pruning intensity (the first pruning lift), the pruned height at 6 years of age was also significantly different for all treatments (p <0.001), and were 0.5, 1.0, 1.9, 2.7, 3.6 and 4.8 m for the treatments ‘U’, ‘8’, ‘6’, ‘4’, ‘2’, and ‘0’, respectively. By repeating treatments at the age of 7 years (the second pruned lift), pruned heights for the different treatments were 0.5, 1.6, 2.7, 3.8, 4.8, and 5.4 m, for the treatments ‘U’, ‘8’, ‘6’, ‘4’, ‘2’, and ‘0’ respectively.

Diameter and height growth after pruning

The growth response after pruning in diameter and height for the different periods after pruning is given in Fig. 3 and Fig. 4, respectively.

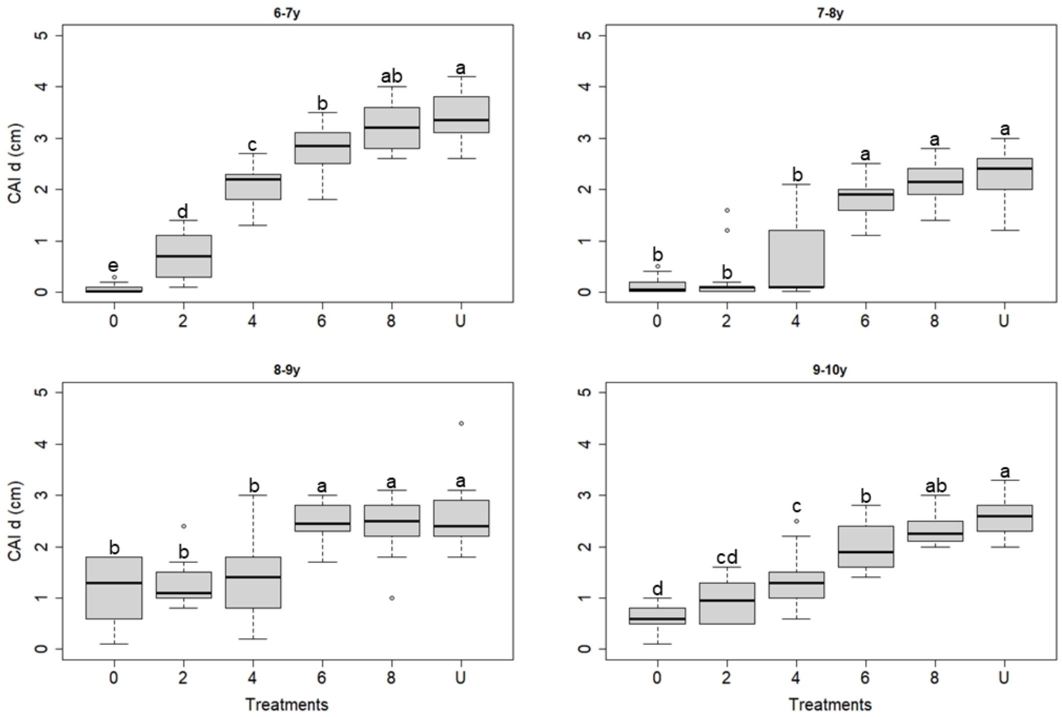

Figure 3. Current annual increment in diameter (CAI d) for the different periods after pruning: the first year, 6-7 years; the second, 7-8 years; the third, 8-9 years; and the fourth, 9-10 years. Treatments named ‘0’, ‘2’, ‘4’, ‘6’, and ‘8’ indicate the number of whorls left after pruning conducted at the age of 6 years; ‘U’ – unpruned as the control. The bold line indicates the median of the data, while the grey box reflects the interquartile range between first (25th) and third (75th) percentiles. Outliers are given as circles. Treatments with the same letter do not significantly differ (Tukey, α = 0.05).

Figura 3. Incremento corrente anual em diâmetro (CAI d) para os diferentes períodos após a poda: o primeiro ano, 6-7 anos; o segundo, 7-8 anos; o terceiro, 8-9 anos; e o quarto, 9-10 anos. Tratamentos nomeados como ‘0’, ‘2’, ‘4’, ‘6’ e ‘8’ indicam o número de verticilos remanescentes após a poda realizada na idade de 6 anos; ‘U’ – não podado. A linha em negrito indica a mediana dos dados, enquanto a caixa cinza a amplitude de variação dos dados entre o primeiro (25) e o terceiro (75) percentis. Dados discrepantes são apresentados como círculos. Tratamentos com a mesma letra não diferem estatisticamente (Tukey, α = 0,05).

It was observed that pruning intensity highly influenced tree diameter growth, already in the first year after pruning and during all the period analyzed, 6-10 years of age (p <0.001, for all periods). In the period between 6-7 years of age, the year immediately after pruning, a great differentiation in diameter growth was detected. Only trees with 8 remained whorls (treatment ‘8’) were able to grow similarly to the unpruned ones (treatment ‘U’), both with an increment level >3 cm yr^{-1}. Tree growth linearly decreased as fewer whorls were kept after pruning, being as low as 0.08 cm for trees with ‘0’ whorls. During the second period after pruning, and as a combined result of two pruning lifts, ages 7-8 years, differences were still significant but less differentiated. In this period, trees with at least 6 whorls were able to grow as much as trees with 8 and those that were unpruned. Meanwhile, trees with 4 whorls or less grew similarly to those of treatment ‘0’. The same differentiation was observed in the third year (8-9 years). In the fourth period, ages between 9-10 years, results were similar to the ones verified in the first period, when only trees with 8 whorls were able to grow at levels similar to those delivered by unpruned trees (>2 cm yr^{-1}).

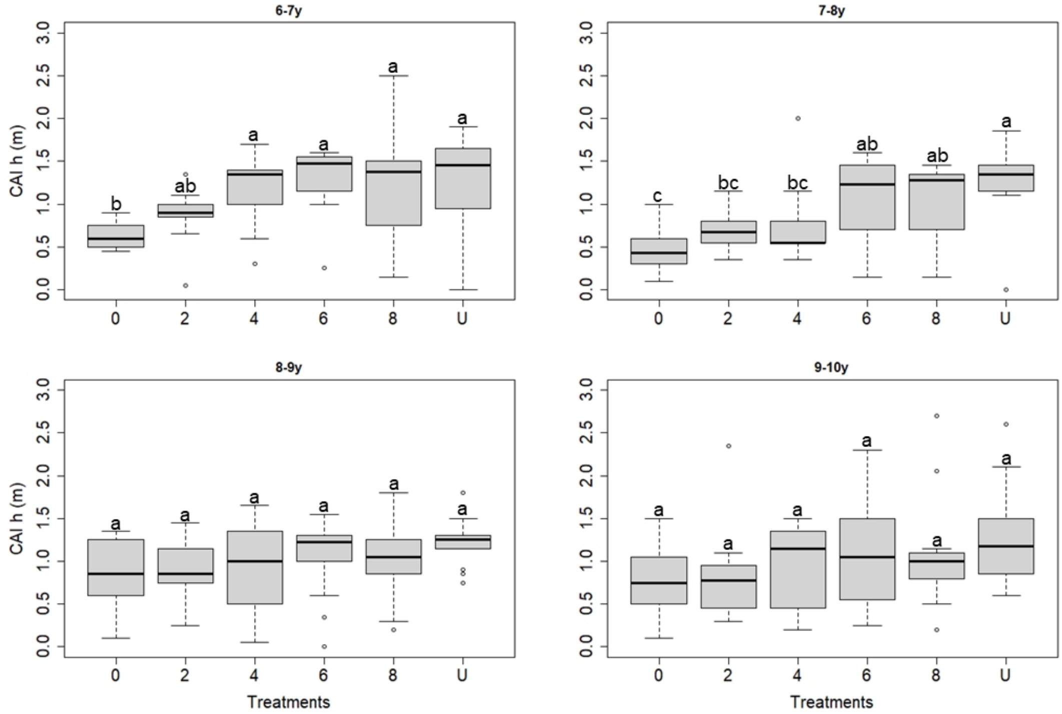

Figure 4. Current annual increment in height (CAI h) for the different periods after pruning: the first year after pruning, 6-7 years; the second, 7-8 years; the third, 8-9 years; and the fourth, 9-10 years. Treatments named ‘0’, ‘2’, ‘4’, ‘6’, and ‘8’ indicate the number of whorls left after pruning conducted at the age of 6 years; ‘U’ – unpruned as the control. The bold line indicates the median of the data, while the grey box reflects the interquartile range between first (25^{th}) and third (75^{th}) percentiles. Outliers are given as circles. Treatments with the same letter do not significantly differ (Tukey, α = 0.05).

Figura 4. Incremento corrente anual em altura (CAI h) para os diferentes períodos após a poda: o primeiro ano após a poda, 6-7 anos; o segundo, 7-8 anos; o terceiro, 8-9 anos; e o quarto, 9-10 anos. Tratamentos nomeados como ‘0’, ‘2’, ‘4’, ‘6’ e ‘8’ indicam o número de verticilos remanescentes após a poda realizada na idade de 6 anos; ‘U’ – não podado. A linha em negrito indica a mediana dos dados, enquanto a caixa cinza a amplitude de variação dos dados entre o primeiro (25) e o terceiro (75) percentis. Dados discrepantes são apresentados como círculos. Tratamentos com a mesma letra não diferem estatisticamente (Tukey, α = 0,05).

From Fig. 4, it can be observed that height growth was less affected by pruning than diameter growth. Trees with only ‘2’ whorls left after pruning were able to deliver a similar current annual increment in height as the one observed in unpruned trees (p <0.01, increments of 0.9-1.3 m yr^{-1}). Although a higher differentiation was detected at ages 7-8 years, as a combined effect of both pruning lifts, it disappeared afterward in the following periods, when no differences were observed, and all trees grew at levels around 1 m yr^{-1}.

The dynamic effect of pruning intensity on the diameter growth along the years is presented in Fig. 5. Although the previous figures already clearly presented the negative effect of severe pruning on the growth of *A angustifolia* trees, mainly in diameter but also in height, the results shown in Fig. 5 dynamically deliver this aspect. The slope coefficient obtained for the treatments ranged between 0.5-2.7, with the lowest for treatment ‘0’ and highest for treatment ‘U’, robustly indicating how negatively affected diameter growth is as a result of severe pruning.

For treatment ‘2’ and ‘4’, it is possible to visualize the reaction of trees in diameter growth as a result of rebuilding crowns after subsequent height growth. In treatment ‘2’, this reaction is clearer for some individuals from year 9 onwards, i.e., trees took two years after the pruning lifts to rebuild crowns and deliver higher levels of diameter increments. For treatment ‘4’, trees seem to have been more negatively affected by the second pruning lift when diameter values remained stable from year 7 to 8 years. Again, at the age of 9 years, two years after the second pruning lift, some individuals were able to rebuild their crown and deliver higher diameter increments.

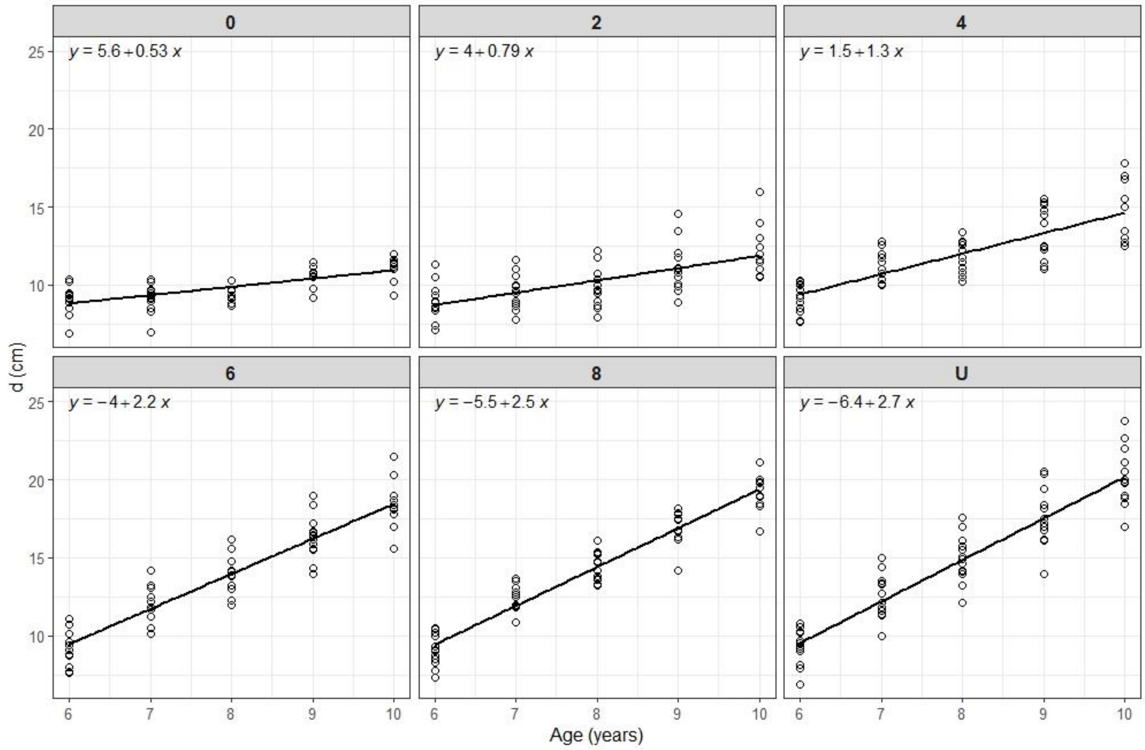

Figure 5. Diameter (d) development between ages 6-10 years. Treatments named ‘0’, ‘2’, ‘4’, ‘6’, and ‘8’ indicate the number of whorls left after pruning; ‘U’ – unpruned as the control. The linear trend and its equation for each treatment are also given.

Figura 5. Desenvolvimento em diâmetro entre as idades de 6-10 anos. Tratamentos nomeados como ‘0’, ‘2’, ‘4’, ‘6’ e ‘8’ indicam o número de verticilos remanescentes após a poda realizada na idade de 6 anos; ‘U’ – não podado. A tendência linear e sua equação são apresentadas para cada tratamento.

Pruning quality

Pruning quality was exploratorily assessed due to a destructive analysis, which allowed for determining the dimension of the defect core at different heights. The defect core was determined after the average and maximum radii measurements. By regarding the average radii, the diameter of defect core implies an average potential for obtaining knotty-free timber due to sawn processes. On the other hand, the maximum radii for the determination of defect-core diameter is a more realistic approach, especially for rotary peeling in which veneers are not knotty-free as soon as the biggest defect-core point is reached within the log length. The different analyses of pruning quality are given in Fig. 6.

From Fig. 6-a, it can be observed that the diameter of defect core regarding the maximum radius reached an average of ~14 cm, varying between 9-18 cm within the first 2 m of height. This variation is a result of different tree diameters at the moment pruning was carried out. Dominant trees had higher defect cores than intermediate ones. From 2 m of height upwards, the lower defect core diameters are the result of the more intense pruning treatments. Fig. 6 also shows the result of a successful pruning procedure (Fig. 6-b), the fast occlusion process (Fig. 6-c) on the transversal and longitudinal planes, which lasted no more than the year following pruning and, finally, the result of a late pruning (Fig. 6-d).

At the moment trees were 25 years old, the diameter of defect core was, on average, 50% of the tree diameter at each respective height, ranging between 25-70% of the cross-sectional section.

DISCUSSION

In relation to the pruning intensity, treatments named after the number of whorls left had 0-4 m of remaining crown. Percentage of total height is frequently used as an index of pruning. In this regard, treatments named ‘0’, ‘2’, ‘4’, ‘6’, and ‘8’ had a very didactic remaining crown percentage of 20, 40, 60, and 80% of the total height, respectively. The unpruned trees, treatment ‘U’, had an average live crown equal to 90% of the total tree height. It is important to note that this was the condition immediately after pruning. During the years that followed the pruning procedures, trees grew in height and, therefore, built bigger crowns, while some basal branches might have died in this process.

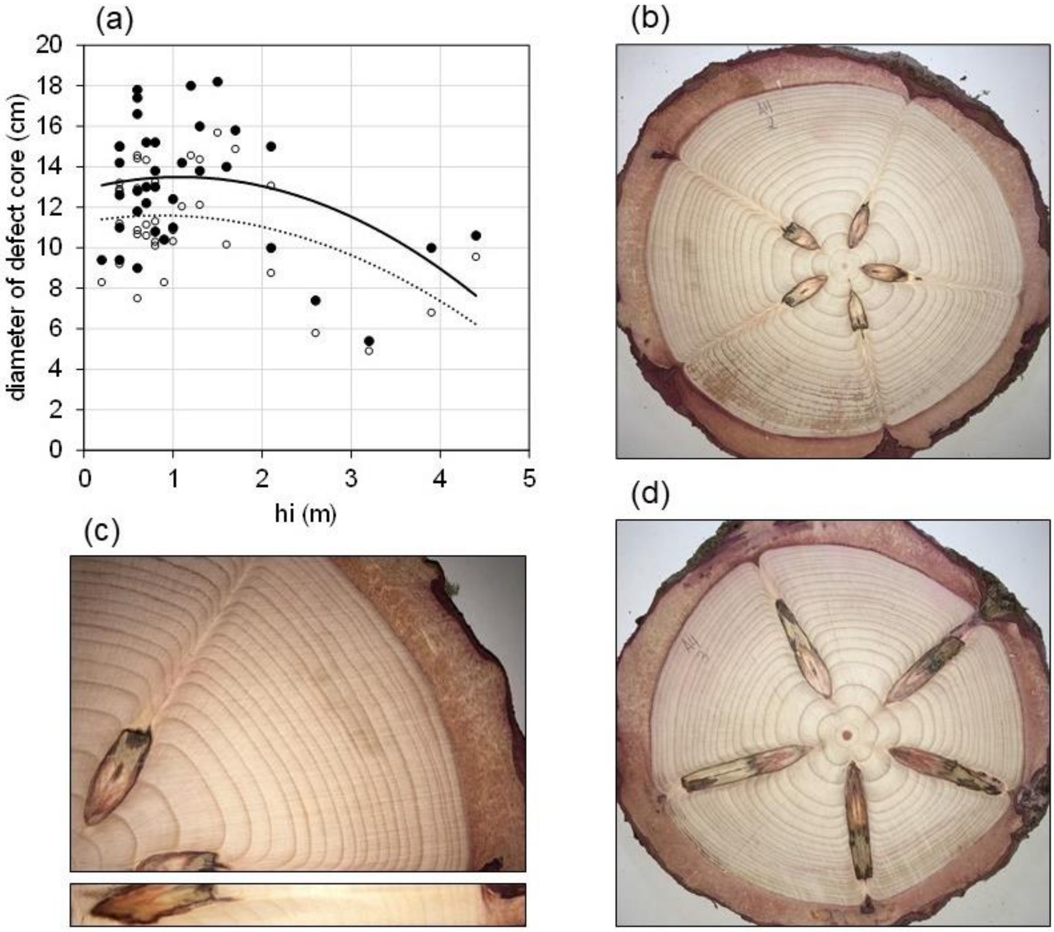

Figure 6. Pruning quality analyses: (a) determination of the defect core diameter at different heights regarding the average of all defect radii per disc (pointed line) and the maximum defect radius (full line); (b) a successfully pruned example resulting in a defect core of 9 cm in diameter at 0.6 m of height; (c) occlusion details on the transversal (above) and longitudinal planes (below), showing it occurs within the first year after the pruning procedure when carefully conducted; and (d) a cross-sectional disc collected at 1.7 m height, over the pruned height for this individual in the experiment and pruned only several years after when a tree was 12 years old, showing the ~10 years incorporation of dead branches, before they were lately pruned.

Figura 6. Análises qualitativas da poda: (a) determinação do diâmetro do núcleo defeituoso nas diferentes alturas considerando a média de todos os raios defeituosos por disco (linha pontilhada) e o raio defeituoso máximo (linha cheia); (b) um exemplo de poda bem sucedida resultando um núcleo defeituoso de 9 cm de diâmetro a 0,6 m de altura; (c) detalhes da oclusão do galho podado nos planos transversal (acima) e longitudinal (abaixo), demonstrando que ela ocorre durante o primeiro ano após a poda quando realizada de forma cuidadosa; e (d) uma seção transversal amostrada a 1,7 m de altura, acima da altura de poda para este indivíduo no experimento e podado somente alguns anos depois, quando a árvore apresentava 12 anos de idade, demonstrando os ~10 anos de incorporação de galhos mortos antes deles terem sido tardiamente podados.

Because height growth was less affected than diameter growth after pruning, optimal pruning intensity should place greater emphasis on the second one. As already pointed out, only by keeping ‘8’ whorls after pruning, trees were able to deliver unaffected diameter growth during the whole period analyzed. Thus, this can be considered an optimal intensity for no diameter growth losses. By keeping ‘6’ whorls, trees oscillated in delivering unaffected and affected diameter growth rates.

It is important to note that by keeping ‘8’ whorls left after pruning, the pruned height was 1.0 m, while keeping ‘6’ whorls, the pruned height shifted up to 1.9 m. By repeating the pruning treatments at the age of 7 years, the total pruned height was 1.6 m for the treatment ‘8’, a second lift of 0.6 m, and 2.7 m for the treatment ‘6’, a second lift of 0.8 m. In the treatment ‘4’, a total pruned height of 3.8 m was obtained, however, with intense reduction of diameter growth. This is essential information for when operational and economic aspects are also regarded in determining optimal pruning strategies.

As no previous studies related to pruning *A. angustifolia* could be found, some comparisons to the genus *Pinus* are given as follows. Hoppe and Freddo (2003) studied different pruning intensities in *Pinus elliottii* Engelm. in the state of Rio Grande do Sul, Brazil. The authors concluded that pruning over 40% of the trees total height strongly influenced diameter and volume growth.

Neilsen and Pinkard (2003) studied *Pinus radiata* trees grown in Tanzania pruned at the age of 6 years up to 2.4 m. At the ages of 8 and 10 years, trees were pruned again to 45, 60, or 75% of tree height, and growth was compared with trees subjected to the first lift only. Pruning to 45% had no effect on growth, while pruning to 60 or 75% reduced diameter increment until measurement ceased at 17 years. The authors also concluded that the effect of severe pruning on diameter growth was greater for subdominant trees than for dominant ones. Additionally, they reported that pruning had less effect on height than in diameter, similar to the verified in the present study. The reduction in diameter or basal area was more marked than height growth also for *P. radiata* grown in New Zealand (MEAD, 2013).

The remaining crown length in the present study for the treatment, which kept '8' whorls, was 4 m, the only one capable of growing similarly to the unpruned trees. The 4 m of remaining crown was equal to 80% of the tree height at the age of 6 years. This is an important aspect, since percentages around 50% are frequently reported for other tree species. Anyhow, this study reinforces the need of regarding also absolute values of remaining crowns instead of only relative ones which may be biased depending on tree age.

Ferrere *et al.* (2015) evaluated the effect of pruning *P. radiata* grown in Argentina. The authors concluded that the removal of 40% of the live crown at the age of 6 years (d_g = 11-13 cm), resulted in a pruning height of 5 m in average, and presented a negative influence in diameter growth of 5-6% in relation to unpruned stands. The conclusions were obtained when the stands were 13 years old.

Because clear wood is only obtained after complete occlusion, the knotty-core is also called defect-core to incorporate not only the knots but also the healing or occlusion zone. In the present study, defect cores of ~14 cm were detected (9-18 cm) or 50% of tree diameter (25-70%) at the age of 25 years. Results indicated that a 15 cm of defect core is a feasible target for *A. angustifolia*. This can be achieved by keeping 6-8 whorls after pruning, so diameter growth is not, or only slightly, affected. For the stand evaluated in this study, it would be a pruning lift of 1.0-1.9 m at 6 years of age, and 1.6-2.7 m at 7 years of age. However, special attention should be given for dominant trees, or the potential crop ones, since defect cores up to 18 cm were observed, indicating these trees should have been pruned earlier if the target was to be kept to a maximum of 15 cm. Regarding the well-known rule that the defect core should not represent more than 1/3 of the small-end diameter of logs, allowing the defect core to reach 18 cm would imply an additional 9 cm in the small-end diameter of logs for reaching industrial standards and pruning premium prices.

Mead (2013), reported for *Pinus radiata,* as a rule of thumb, the defect core is about 6 cm greater than the diameter over stubs for straight logs. Thus, if the maximum diameter over stubs is 18 cm, the diameter of the defect core is about 24 cm. In other words, for *P. radiata,* the occlusion zone takes 3 cm to start clear wood production. Although not quantitatively determined for *A. angustifolia* in the present study, it can be stated that it took no more than 1 cm at each pruned branch, i.e., no more than 2 cm in diameter, especially for pruning green branches. It is important to note that pruned branches were relatively small since pruning started when *A. angustifolia* trees were 6 years old, and the pruned itself was carefully conducted. This experiment showed, therefore, that it is possible to achieve fast occlusion processes, but it is certainly a challenge to keep this quality under commercial operations. Even exploratorily observed, some discs revealed how slow occlusion process could be a result of pruning big dead branches, or due to poor cutting techniques.

Because high pruning is costly, and because many trees in a stand are thinned out before rotation age, only some trees should be selected for pruning. These are trees of good form, vigorous growth, and which are likely to constitute the final crop. Knowing the optimal pruning intensity is especially important in such stands, where only selected trees are pruned, so the effect of temporarily depressing growth is concentrated only in the potential crop ones. Meanwhile, the unpruned trees may keep growing at higher levels and, therefore, will impose higher competition levels. Moreover, it is important to note that pruning should be done in association with thinning, so that pruned trees are favored, as was the case in this study.

Finally, it is important to note that there are trade-offs between the size of the defect core, the number of pruning lifts, and accepting some degree of growth reduction. The result of the present study indicated that it is advisable to keep 8 whorls left after pruning if diameter growth is not to be negatively affected. However, optimal pruning schedules may regard a minimum of '6' whorls to compromise all those aspects, including the operational and economic ones. For the evaluated site index, to start pruning at the age of 5 years seems to be important for keeping defect cores under a feasible target of 15 cm, especially for the dominant trees.

CONCLUSIONS

From the results obtained in the present study, it is concluded that:

- Pruning intensity can have a significant negative effect on the growth of young *A. angustifolia* trees. Diameter is more affected than height growth.
- Pruning young *A. angustifolia* trees for knotty-free timber production must be conducted keeping 8 whorls after the intervention if no negative effect in current annual increment in diameter is to be observed when compared to unpruned trees.
- A defect core of 15 cm seems to be a feasible target for the species regarding optimal pruning intensities, which avoid diameter growth losses. However, this is strongly dependent on a fast occlusion process, which, in turn, is a result of a careful pruning technique.

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