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Recommended thinning regimes for Araucaria angustifolia plantations on small properties in southern Brazil – a case study

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Abstract
Araucaria angustifolia has economic and productive potential in southern Brazil, due to its high wood quality and seeds appreciated by humans and wild animals, besides playing an important role in the rehabilitation of degraded areas. Moreover, the species represents an opportunity of higher incomes for small farmers through the establishment of plantations in small lots managed for timber production. However restrictive environmental laws, and little knowledge about the silviculture of the species has led to a lack of interest in planting and in developing new researches on A. angustifolia. So the objective of this research was to better understand the outcomes of management systems used in A. angustifolia plantations and to evaluate the feasibility of establishing araucaria plantations on small farms. For this purpose, we carried out an inventory in an 8-year-old, 0.92 ha araucaria plantation, with a spacing of 3 x 3 m, in Rio Negro, Paraná, Brazil. Based on the results, we used the SisAraucaria software to simulate thinning regimes, varying in age and type of thinning (only selective, only systematic or both), and clear cut at age 25. The regimes with two selective thinning episodes were more productive than those with only one or no thinning. The best economic return was obtained with the regime that included thinning at 10 and 20 years, with the first removing 80 % of the trees and the second 20 % of the trees. We conclude that the plantation model evaluated may be feasible if the appropriate thinning regime is applied.
Keywords: Management diagram; Parana pine, growth

Introduction

Araucaria, Brazilian pine or parana pine (*Araucaria angustifolia* (Bert.) O. Ktze) is the main native conifer in Brazil. The species gives its name to the Araucaria Forest (Mixed Ombrophilus Forest), and its natural range crosses several states in Southern Brazil. Timber production, along with the growing need for agricultural land and pasture, led to large-scale exploitation and destruction of these forests (Nutto *et al*. 2005). By the year 2000, Guerra *et al*. (2002) estimated that only 400,000 hectares of this forest type remained.

Currently, any commercial exploitation of these species is prohibited (Brasil 2006). As such, landowners are reticent to let araucaria grow; they tend to remove any seedlings that naturally regenerate on pastures or forest edges and illegal felling of the trees has become a common practice.

In rural areas across the native range of the species, there is a clear lack of new araucaria plantations. The few existing commercial araucaria plantations, which currently total little more than 11,000 hectares (ABRAF 2013), and reductions in the rate of planting because of confusion over current legislation, has resulted in a lack of interest in developing new research on the species. In general, the plantations that do remain are not managed and their production is stagnating, creating an image of the species that is inconsistent with its actual importance and viability (Santos *et al.* 2010). Uncertainties related to the bureaucratic processes involved in harvesting and transport, including confusion around obtaining permits, are also an issue.

Considering the high value of the wood, as one cubic meter for standing trees with diameter at breast height (DBH) greater than 40 cm could reach a price of US$ 100 (SEAB 2012), as well as the diverse end uses of the species, araucaria can provide numerous economic advantages for agricultural producers (Pinto 2009). As the dominant forest species in Southern Brazil, *Araucaria angustifolia* plays a significant role in rural communities; its seeds are consumed by both humans and animals, representing an important source of food during the winter (Stefenon *et al.* 2007); the harvesting and selling of these seeds provide extra income for smallholder farmers. It could also be used in restoration programs for degraded areas, considering that the establishment of plantations facilitates forest regeneration in grassland faster than natural succession (Zanne and Chapman 2001). Monocultures are not intrinsically poor in terms of biodiversity, and especially Araucaria plantations can refuge 49% of species found in natural Araucaria Forest neighboring (Fonseca et al. 2009). Zurita *et al.* (2006) observed that Araucaria and Pine plantations supported more than 60 % of the bird species naturally occurring in Araucaria Forest, mainly forest-generalist and edge species.

With the objective of providing information about growth in araucaria plantations, the SisAraucaria software, developed by Embrapa Forestry, with support from the company Klabin S.A., Southern Brazil, simulates management of the species. The database used to inform the simulations is developed from the results of successive inventories in plantations older than 60 years that represent the growth evolution and productive capacity of inventoried areas. According to Oliveira (2011) the statistical methods were based on SB and SB bivariate (SBB) distributions to describe the marginal distribution of diameter and height of trees in stands of different ages and the joint distribution of both variables.

The definition of the most advantageous thinning regimes requires the testing of different scenarios, determining whether to yield greater production in volume and/or better economic returns. One alternative is to simulate regimes considering the plantation density interval appropriate for thinning, defined by the density management diagram (DMD) for the species. The DMD shows the relationship among basal area, number of trees per hectare, and the diameter of the tree with the average stand basal area. Although DMDs do not provide information on the best age to execute thinnings, it is possible to plan them considering the number of trees and the quadratic diameter and their corresponding position in the DMD.

Along with technical criteria that aim to make better use of the productive capacity of the site and species, we must consider economic indicators that evidence the best thinning regime also from the economic point of view. For the economic evaluation, the annualized net present value for a minimum rate of attractiveness and the internal rate of return are generally used.

The objectives of this study are to broaden our understanding of the management of *Araucaria angustifolia* plantations by simulating their production and evaluating the technical viability and economical outcomes of establishing araucaria plantations on small properties, while also testing the applicability of the density management diagram previously developed for the species. We intend to confirm the hypothesis that it is feasible for a small farmer to plant araucaria, although its growth is not yet as notable as that of other gymnosperms species planted commercially in Brazil. Therefore it is necessary to adopt an appropriate thinning regime, which we must know beforehand.

Material and Methods

The araucaria plantation analyzed in this study has an area of 0.92 ha and was established in 2006 with a spacing of 3 x 3 m. It is located in Rio Negro Research Station of the Federal University of Paraná, in the municipality of Rio Negro, Paraná, at an altitude of 788 m above sea level (26° 04' 02.40" S and 49° 45' 58.76" W). The climate in the region is characterized as temperate (Cfb), with average temperatures during the coldest month lower than 18 ºC (mesothermal), cool summers with an average temperature in the hottest month below 22 ºC, and no defined dry season. The average annual precipitation is between 1,400 and 1,600 mm, and the average annual relative humidity is between 80 and 85 % (Caviglione *et al*. 2000). Based on Bhering and Santos (2008), soils in the region are classified as Entisols.

The data used in the analyses came from an inventory conducted at the site when the trees were eight years old. At that time, eight plots with varying sizes of 290, 580, 690, 671, 653, 653, 644 and 554 m^2 were installed, representing a sampling intensity of 51 %. Each plot has a different area because it covers four complete rows of trees and the planting area is uneven, not a perfect square or rectangle.

In the plots, we measured the circumference at breast height (CBH) for all trees with a measuring tape, and the total height of 60 % of the trees using a telescopic ruler. Using this data, we were able to adjust four hypsometric models through regression analysis. Stem volume was estimated using a volume equation selected from ten equations adjusted with data from 19 standing trees of the stand. We selected perfect trees that represented the diametric range found in the sample plots. The trees were measured using the Criterion RD1000 dendrometer which is able to measure diameter at different heights of the stem, and we calculated the volume using the Smalian method.

The measured results for basal area, number of trees per hectare, and age at date of measurement in the stand were used to simulate thinning regimes in the SisAraucaria software. Site index was calculated considering the dominant height at 8 years old, thus resulting on the dominant height for an index age, in this case 15 years. Site index was estimated by equation 1 (Oliveira 2011).

$$S = HD \times \exp\left(\left(-4.2327 \times \left(\left(\frac{1}{15}\right)^{0.48} - \left(\frac{1}{A}\right)^{0.48}\right)\right)\right) \quad [1]$$

Where, S = site index, A = age when inventory was carried out (years), HD = dominant height at age when inventory was carried out (meters).

In SisAraucaria the total volume of each tree was calculated by a form factor that we calculated from trees of the stand, and the volume per assortment was obtained by a compatible taper function, a fourth-degree polynomial shown in equation 2 (Oliveira 2011).

$$d_i = DBH \times \left(0.080127 + 1.038552 \times \left(1 - \frac{h_i}{H}\right) + 1.6698 \times \left(1 - \frac{h_i}{H}\right)^2 - 4.21279 \times \left(1 - \frac{h_i}{H}\right)^3 + 2.525275 \times \left(1 - \frac{h_i}{H}\right)^4\right) \quad [2]$$

Where, d_i = diameter at height h_i (cm), DBH = diameter at breast height (cm), h_i = height at which point the diameter is to be estimated (m), H = total height (m).

However, before running the thinning simulations in SisAraucaria, we manually performed simulations for each plot, considering the spatial distribution and physical characteristics of the trees. We considered that the stand evaluated in this case study represents a small and special area, where the seedlings were originated from pre-germinated seeds planted directly on the site instead of being produced in the nursery. There was a replanting about 15% of the seedlings six months after planting, and a second replanting about 5% of the seedlings one year after the first replanting. In addition, in the last 12 planting lines (out of 63 lines) the terrain is excessively humid, subject to flooding during certain months of the year, what contributed to a slower growth of the trees and even death of some of them. Under these conditions it would be possible that SisAraucaria could not adequately carry out the production prognosis, a fact that should be evaluated.

Then we defined thinning regimes considering usual practices in commercial plantations of exotic species. We calculated the volume, basal area, and total number of trees (remaining and thinned) per hectare, for five thinning regimes: (1) systematic, every 4^{th} row, representing 33.3 % of living trees; (2) systematic, every 5^{th} row, representing 26.2 % of living trees; (3) systematic, every 4^{th} row, and selective, equaling 43.1 % of removed trees; (4) systematic, every 5^{th} row, and selective, equaling 43.5 % of removed trees; and (5) selective, removing 42.6 % of trees with the lowest DBH.

The regimes with systematic thinning considered all four possible combinations of rows to be thinned in the stand. The choice of the best type of thinning regime to be adopted in the area was based on the simulated outcome in the plantation after thinning. We chose the regime that presented the highest remaining volume for the same quantity of remaining trees. This thinning regime would also allow the trees of better quality to remain.

After defining the type of thinning to be adopted (only selective, only systematic or both), considering the manual simulations, we tested six scenarios, trying to define the moment to schedule the first and the second thinning, because the previous simulations were carried out at 8 years old, at the date of the inventory. So we considered the maximum stand density index (SDI) for *A. angustifolia* obtained by Loureiro (2013), 1400, and the mean quadratic diameter should be at least 16 cm before the first thinning and at least 20 cm before the second thinning in order to remove wood of some commercial value, adopting the usual practice in commercial plantations of other species. Thus in the six scenarios, SDI assumed values between 406 and 580 before the first thinning (29 to 40% of maximum SDI) and between 443 and 606 before the second thinning (31 to 43% of maximum SDI). These values took into account the approach of Long (1985) that states that the minimum limits for full site occupation and self-thinning would be respectively 35 and 60% of the maximum SDI of some species of conifers; he also considered that the beginning of the competition between the trees must occur with 25% of the maximum SDI of the species. With the objective of calculating SDI before thinning we adopted the equation [3] previously proposed by Tang *et al.* (1994) and further developed by Loureiro (2013) for *Araucaria angustifolia*, considering overstocked forests, in a spacing of 1.5 x 1.5 m.

$$\mathrm{Ln(SDI)} = \mathrm{Ln}(\mathrm{N_t}) + \frac{1}{1.7153} \times \mathrm{Ln}\left[\left(\frac{\mathrm{d_t}}{25}\right)^{2.1679\times1.7153} - \delta\right] \quad [3]$$

Where: t = age of the stand; Nt = number of trees per hectare at age t; dt = mean quadratic diameter at age t; 2.1679 = β = parameter of maximum selfthinning rate for complete density; 1.7153 = Y = selfthinning index.

Additionally, we simulated in SisAraucaria a further 117 scenarios of varying ages and thinning intensities, although they are independent of the prescriptions of DMD referent to basal area. These scenarios considered all possible combinations of three different ages for the first thinning (at 10, 12 or 14 years), three different ages for the second thinning (at 16, 18 or 20 years) and four different thinning intensities (removal of 30, 47, 63 or 80 % of the trees) applied in both occasions. The clear cut was fixed at 25 years old for all scenarios.

The economic analysis considered the Annualized Net Present Value (ANPV) for a minimum rate of attractiveness of 4 %, which remunerates the present average annual inflation rate in Brazil – 3,7 % as estimated by Banco Central do Brasil (2017), for year 2017 – and an Internal Rate of Return (IRR). The costs were estimated based on values used in the region for plantations of other species and the prices were based on the actual value of pine stems, adding 25 % for log grades with a diameter greater than 25 cm, considering that there has been a market for araucaria stems in the region (Table 1).

Table 1. Costs and prices considered in the economic analysis of thinning regimes, for the average monthly exchange rate R$ to US$ = 3.27 (2016, July)

Items considered	Costs (US$ ha^{-1})	Grade (Log diameter and length)	Price of standing timber (US$ m^{-3})
Seedlings	237.83	8 to 18 cm, 2.40 m	11.93
Replanting	28.54	18 to 25 cm, 2.40 m	24.46
Land preparation	458.67	25 to 35 cm, 2.60 m	53.52
Weed removal year 0	171.25	> 35 cm, 2.60 m	66.36
Weed removal year 1	85.63		
Weed removal year 2	42.81		
Ant control	18.35		
Land value	3159.02		

Results

The results from the adjusted hypsometric models indicated a parabolic model (Table 2) best represents the relationship between DBH and height in the study area. We then used the model to estimate the height of trees not measured in the survey. It is important to note that we recommend the use of this model only for trees with a diameter range similar to that included in this study.

Table 2. Hypsometric model fitting results and accuracy for evaluated hypsometric models

Name	Equation	R²	R² adj.	Syx	Syx(%)
Parabolic	h= -0,303507875+0,922453831×d-0,019431983×d²	0.8591	0.8581	0.7200	9.54
Henricksen	h= -3,506736895+4,62201464×Ln d	0.8431	0.8425	0.7585	10.05
Stofells	Ln h= 0,073148129+0,796452545×Ln d	0.8801	0.8797	0.7717	10.26
Curtis	Ln h= 2,51914878-5,414142622×1/d	0.8348	0.8342	0.8262	11.06

h= height (m), d = diameter at breast height, DBH (cm).

For volume, Meyer´s model presented the best statistical estimates and the most homogeneous distribution of residuals. However, we selected Spurr´s model, the second best model (Table 3), which was more robust as it provided adequate estimates even for some trees that were not considered in the range covered by the volume equation.

Table 3. Model fitting results and accuracy for evaluated volumetric models.

Name	Equation	R² adj	Syx	Syx (%)
Spurr	v=0,018142+0,000037×d²×h	0.9135	0.0153	16.47
Parabolic	v= 0,047703-0,007970×d+0,000764×d²	0.9037	0.0162	17.38
Kopezky - Gehrhardt	v= -0,002270+0,000471×d²	0.9013	0.0164	17.60
-	v=0,000462×d²	0.9230	0.0160	17.06
Dissescu – Meyer	v= -0,000645×d+0,000502×d²	0.9188	0.0163	17.58
Husch	Ln v= -7,708728+2,002241×Ln d	0.8738	0.0175	19.11
Schumacher and Hall	Ln v= -8,157856+1,145331×Ln d + 1,219939 × Ln h	0.8856	0.0175	19.08
Spurr – logarithmic	Ln v= -8,007004+0,744389×Ln(d²×h)	0.8895	0.0161	17.58
Schumacher - Hall semi logarithmic	v= -0,292474+0,123341×Ln d+0,031293×Ln h	0.7581	0.0257	27.55
Meyer	v= -0,303933+0,016073×d+0,000522×d²-0,008222×d×h+0,000203×d²×h+0,081627×h	0.9157	0.0151	16.26

v = volume (m^3), h = height (m), d = DBH (cm)

The average dendrometric variables indicated a DBH of 12.2 cm, minimum 2.1 cm and maximum 19.7 cm, with a distribution of frequency showed in Figure 1, height of 7.9 m, minimum 1.52 m and maximum 11.10 m. Small trees – diameter less than 6 cm – were found in the 12 last lines due to excessive soil moisture and even flooding at certain times of the year.

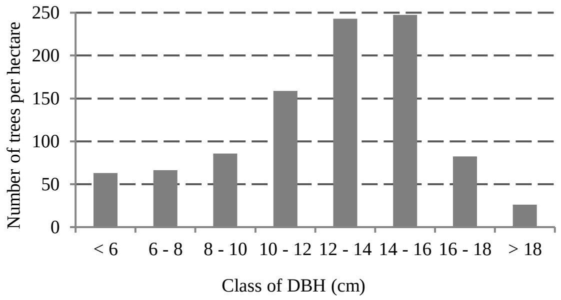

Figure 1. Distribution of number of trees per hectare per class of diameter

Other dendrometric variables values were transversal area of 0.0128 m^2 $tree^{-1}$, mean quadratic diameter (Dq) of

12.8 cm, basal area of 12.5 m^2 ha^{-1}, and volume of 68.8 m^3 ha^{-1} for 973 trees ha^{-1}. The coefficient of variation for volume was 17.1 % which can be justified by the fact that the population is still young and in development. This heterogeneity was also reflected in the sampling error of 14.3 % (95 % probability, t=2.365).

The form factor of the trees with DBH greater than 10 cm was on average 0.59, ranging between 0.47 and 0.76 (Figure 2). Similar results were obtained by Figueiredo Filho *et al.* (2014) for the same age by adjusting the equation to represent the development of the form factor throughout the lifecycle in plantations of more than 40 years and by Sanquetta *et al.* (2016) for sixteen-year-old plantations.

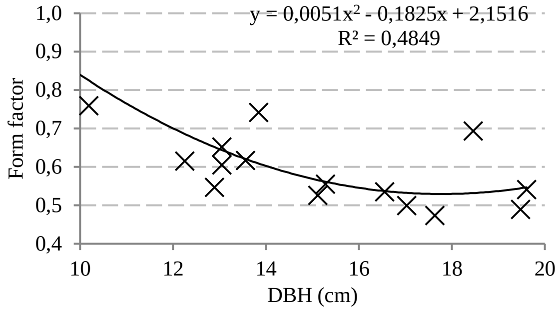

Figure 2. Form factor of trees with DBH greater than 10 cm.

The mean annual increment (MAI) in volume was 8.6 m^3 ha^{-1} year^{-1} at eight years, or 0.00883 m^3 year^{-1} in average per tree for DBH equal to 12.2 cm. In comparison with the growth of *Pinus taeda* in Southern Brazil, which reaches MAI volume values at eight years between 11.7 to 28.6 m^3 ha^{-1} year^{-1}, based on data adapted from biomass at different locations (Munhoz 2011), the initial growth of araucaria found in the study area is slow.

As the dominant height of the population at eight years was 9.7 m, the site index calculated using the adjusted equation for SisAraucaria was 14.6 m, suggesting a site with intermediate productivity, based on the table of site indexes presented by Oliveira (2011). This site index was used to predict growth in SisAraucaria.

The comparison between the results simulated by SisAraucaria for the age of the inventory and the actual inventory results shows that the volume predicted by the software was 9.2 % lower than that estimated from the inventory by the equation and only 1.6 % lower than that estimated from the inventory, using the same form factor, 0.59 (Table 4), for the same basal area and number of trees per hectare. Differences between the results are acceptable, since SisAraucaria works on a database of successive inventories carried out in a given area, and in this work, its results are being compared with the result of a specific experiment, which does not yet undergo a continuous inventory due to its young age. Therefore, this difference should be also expected for estimates at future stages when using the SisAraucaria software, but it should be emphasized that the thinning regimes evaluated are merely theoretical, so there is no evidence of growth responses after thinning in this area.

Table 4. Results of the inventory and the SisAraucaria projection at eight years of age

Method	Dominant height (m)	N (trees ha^{-1})	Dq (cm)	Average height (m)	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})
Inventory (equation)	9.7	973	12.8	7.9	12.5	68.8
Inventory (form factor)						63.5
SisAraucaria	9.7	973	12.8	8.4	12.5	62.5

Although the plantation used in this study did not have the conditions necessary for thinning, as we clearly observed a lack of competition for light between the crowns, we conducted thinning simulations at eight years in the plots. The results indicated that for selective thinning, a removal of 43 % of the trees represents 16 % of the volume, while the same percentage of trees removed using systematic thinning every fourth row and selective in the other rows, represented 27 % of the volume (Table 5).

The results from the different thinning regimes simulated directly for the plots led us to choose a selective thinning regime, removing 43 % of the live trees of the lowest DBH, as it is a plantation with a survival rate of 87.5 %, at 8 years old, according to the results of the inventory. This regime, besides favouring the development of the best trees, would maintain standing trees that hold 15 % more volume than the regime that combines systematic thinning every fourth row and selective thinning.

Table 5. Number of remaining trees and volume in the thinning simulations for the plots.

Type of thinning	Thinning			Outcome		
	Number of trees (%)	Basal area (%)	Volume (%)	Trees ha^{-1}	Basal area (m^2 ha^{-1})	Volume (m^{3}ha)
4th line	33	33	25	730	9.4	51.5
4th line + selective	43	36	27	680	9.2	50.2
5th line	26	26	21	771	9.9	54.6
5th line + selective	44	30	24	678	9.6	52.0
Selective	43	16	16	683	10.7	57.8

On the other hand, the economic analysis for the simulations in SisAraucaria - for the six scenarios considering the DMD and the other 117 regimes - that also considered selective thinning, showed that the best results were achieved combining thinning intensities of 80% and 30% in the first and second thinning, respectively. In an attempt to maintain more standing trees for the clear cut, we have tested another scenario considering a thinning intensity of 20 % for the second thinning, showed as regime number 5 in Table 6. This regime, with two thinning cycles, at 10 and 20 years, maintaining 156 trees per hectare for the clear cut would be the most profitable regime (Table 6). Among the 118 evaluated regimes, along with the initial six proposed, this regime generated the highest ANPV, US$ 160.99 ha^{-1}, for a minimum Internal Rate of Return of 4 % and the highest IRR, 6.16 %.

Two other regimes with two late thinning cycles, when the basal area reached 25 to 28 m^2 ha^{-1}, between 15 and 17 years (regime 2) and 17 and 20 years (regime 3), but maintaining 477 trees per hectare for the final harvest, provided an increase of 26 and 32 % in volume production, respectively. However, in economic terms, these two regimes generated only 35 and 39 %, respectively, of the ANPV that can be achieved using the regime with the best results (regime 5).

Table 6. Total production and production per log grade in volume by thinning regime; regimes 4 and 5 were considered the best among the 118 evaluated after the six scenarios studied initially

Regime	Intervention	SDI before	Basal area ($m^2.ha^{-1}$) before	Age (years)	N ha^{-1} remaining	Volume up to minimum diameter ($m^3.ha^{-1}$/(%)) >25 cm	Volume up to minimum diameter ($m^3.ha^{-1}$/(%)) <25 cm	Total	MAI (m^3 ha^{-1} $year^{-1}$)	ANPV (US$ ha^{-1})	IRR %
1	1st thin.	633	20.7	12	681	-	23.0 (100)	23.0			
	2nd thin.	542	21.2	14	477	-	34.5 (100)	34.5			
	Clear cut			25	0	61.2 (19)	258.0 (81)	319.2			
	Total					61.2 (16)	315.5 (84)	376.7	15.1	37.86	4.60
2	1st thin.	702	25.8	15	681	-	34.0 (100)	34.0			
	2nd thin.	587	25.2	17	477	-	47.9 (100)	47.9			
	Clear cut			25	0	65.4 (20)	258.7 (80)	324.1			
	total					65.4 (16)	339.6 (84)	405.0	16.2	55.84	4.86
3	1st thin.	745	28.7	17	681	-	41.1 (100)	41.1			
	2nd thin.	626	28.5	20	477	-	58.9 (100)	58.9			
	Clear cut			25	0	66.2 (20)	259.7 (80)	325.9			
	Total					66.2 (16)	359.7 (84)	425.9	17.0	63.03	4.95
4	1st thin.			10	516	-	29.1 (100)	29.1			
	2nd thin.			18	361	-	39.8 (100)	39.8			
	Clear cut			25	0	117.7 (40)	174.9 (60)	292.6			
	Total					117.7 (33)	243.8 (67)	361.5	14.5	79.05	5.17
5	1st thin.			10	195	-	58.0 (100)	58.0			
	2nd thin.			20	156	7.3 (36)	13.1 (64)	20.4			
	Clear cut			25	0	202.5 (83)	40.9 (17)	243.4			
	total					209.8 (65)	112.0 (35)	321.8	12.9	160.99	6.16
6	1st thin.	702	25.8	15	681	0	34.0 (100)	34.0			
	Clear cut			25	0	15.0 (5)	286.3 (95)	301.3			
	total					15.0 (4)	320.3 (96)	335.3	13.4	-20.42	3.65
7	1st thin.	745	28.7	17	681	0	41.1 (100)	41.1			
	Clear cut			25	0	14.2 (5)	288.4 (95)	302.6			
	Total					14.2 (4)	329.5 (96)	343.7	13.7	-18.52	3.68
8	Clear cut			25	0	1.2 (0.4)	328.9 (99.6)	330.1			
	total					1.2 (0.4)	328.9 (99.6)	330.1	13.2	-50.89	3.09

MAI= Mean annual increment, ANPV= Annualized net present value, IRR= Internal rate of return, SDI= Stand density index.

Discussion

We can expect a difference of until 9.2% between volume simulations of SisAraucaria and results of harvest volume on thinning and clear cut, which it is acceptable, if we consider that the database adopted in SisAraucaria is formed by inventory results of about 15,000 hectares of plantations up to 60 years, but it is located in the central-north region of Parana, about 300 km away from the study area. And yet the estimate of site index, basal area, mean diameter and mean height were very accurate compared to the inventory results at 8 years.

Our results demonstrate that araucaria plantations can achieve better economic results if a wide spacing between trees is used. In the analyzed plantation, the 156 trees per hectare at final clear cut simulated using the regime with the best economic results would represent a distribution of one tree every 64 m^2, equal to a spacing of 8 x 8 m. In these conditions, the results indicate that it could produce 83 % of its volume through stems with a diameter greater than 25 cm, in clear cut, or 65% of the total volume produced during 25 years. This result corroborates what Toniolo Jr *et al.* (2015) suggested in an analysis of araucaria stems planted at a similar spacing at 24 years. The authors reported a production of 87 % of volume from stems with a diameter greater than 25 cm, for an average tree with DBH equal to 42 cm and height equal to 19 m at 24 years, which are similar to the simulated values for the regime with the best results in the current study, at 25 years.

However, specifically for the study area, a thinning regime that removes 80 % of the trees should be avoided. The historic occurrence of strong winds in the Rio Negro Research Station, which have tended to break trees in other experimental plantations, suggests that it would be more prudent to adopt an initial thinning at a lower intensity of 47 % of trees at 10 years and 30 % at 18 years (regime 4, Table 6), even though it could compromise the economic results of the plantation, with an ANPV of US$ 79.05 ha^{-1} and IRR of 5.17 %.

The two regimes with only one thinning produce slightly more volume in relation to the regime without thinning, from 1,6 % (thinning at age 15) to 4,1 % (thinning at age 17). However, considering the economic analysis, in which we found negative ANPV values not only for the regime without thinning, but also for the two with one thinning, it is economically unviable to manage araucaria plantations with no or only one thinning for a spacing of 3 x 3 m or similar.

We obtained similar results on volume, compared to those of Crechi *et al.* (2009), who report a higher total volumetric production at the age of 21 years for less intense thinning treatments (33% of the trees). In our study, the regimes 1, 2 and 3 that require the removal of 30% of the trees, generated higher volumetric yields when compared to the regimes 4 and 5 with removal prescription of 47 and 80% of the trees, respectively in the first thinning and 30 and 20% in the second thinning, respectively.

The result of regime 5, with two thinnings, produces 2.5 % less volume than the regime without thinning. However, the release of space caused by thinning contributes significantly to the development of the remaining trees, generating 83 % of the assortment volume with a diameter greater than 25 cm, against 0.4 % in this assortment, in the non-thinning regime. Regime 4, which considers a larger number of trees remaining after the second thinning, compared to regime 5, should generate a volume 9.5% higher than the non-thinning regime (8). Both of them generate a positive ANPV output while the non-thinning regime would be economically unviable with an ANPV of U$ -50.89.

The importance of recommending a thinning regime for Araucaria, given the economic results achieved in this study, is confirmed by the results obtained by Keller *et al.* (2008), where the volume per hectare at 35 years is statistically the same for 10 different initial planting densities, between 4444 to 625 trees per hectare in unthinned stands. At the age of 24, the differences between the mean volume per hectare between the 10 densities are no longer significant (Crechi 1996). The extra volume that is not produced at the highest initial densities is lost by dead trees that could have been thinned in previous years.

Still considering results presented by Crechi (1996) up to age 24 years, similar to that adopted in the present study, the initial density of 1111 (3 x 3m) or 1333 (3 x 2.5 m) trees per hectare may be the most indicated considering the volume production per hectare with a minimum diameter of 7cm, 514.7 and 497 $m^3.ha^{-1}$, respectively, which represents a mean annual increment (MAI) for commercial volume of 21.4 and 20.7 $m^3.ha.^{-1}.year^{-1}$ at 24 years. At these densities, mortality is very similar until 12 years of age, around 10 to 12%; however from 18 years on the non-occurrence of thinning increases the mortality in the plantation of greater density.

In all simulated regimes in our study, the MAI for commercial volume at the final age of 25 years ranges between 12.9 and 17.0 m^3 ha $year^{-1}$, and for regime 4 the MAI would be 14.5 m^3 ha $year^{-1}$. This result is different of that one obtained by Crechi (1996), possibly due to site conditions, with a site index of 16.5 m according to SisAraucaria curve (Oliveira, 2011), while our study area has a site index of 14.6 m. Nevertheless it is compatible with that reported by Carvalho (1994), in Colombo, Brazil, at a medium fertility site, where the productivity ranged from 12 to 18 m^3 ha^{-1} $year^{-1}$.

The results found for the study area reflect the conditions of a stand that has been subjected to pruning for the removal of dead branches as protection against possible fires. The diameter growth at eight years is still being influenced by this process, although it should recuperate in subsequent years. In a rapid survey conducted recently in the area, at 10 years of age, we obtained a basal area of 20 m^2 ha^{-1}, indicating an increase of 60 % for this variable in two years. Furthermore, during the survey, we verified that the crowns begin to compete for space and light, suggesting the need for thinning at 10 years, or at the most in the following year.

It is also important to note that although there has been two replantings until after one and a half year, the area under study presents a mortality of 12.5 % at 8 years old, for an initial density of 1111 trees per hectare. Crechi *et al.* (2009) report a mortality rate of 61.6 % at age 21, in unthinned *A. angustifolia* stands at an initial density of 2524 trees per hectare. This denotes the importance of the living space for each araucaria tree, due to its essentially heliophylous and emerging characteristics (Carvalho 1994).

Conclusions

In what concerns the use of the SisAraucaria program, it has proven to be effective in estimating dendrometric variables at the age at which the inventory was conducted. However, volume predictions for the thinning and the clear cut may be underestimated by up to 9.2 %, according to the specific characteristics of the analyzed plantation, in which pruning occurred until eight years of age.

We conclude that the planting of *Araucaria angustifolia* for the production of high value wood on small properties can be viable in the long term if two thinning regimes are adopted for plantations spaced at 3 x 3 m or 3 x 2.5 m as also obtained in adult plantations by Crechi (1996). From an economic point of view, it is preferable and recommended that the first thinning is intense to favor the growth of the remaining trees, but this must take into consideration the local environmental conditions of the plantation. In general terms, we can recommend medium intensity thinnings, suggesting the removal of 47% of the trees in the first and 30% in the second.

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