THINNING FROM BELOW: EFFECTS ON HEIGHT OF DOMINANT TREES AND DIAMETER DISTRIBUTION IN *EUCALYPTUS* STANDS

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This study aimed to evaluate the height and diameter growth of dominant trees in eucalypt plantations submitted to thinning from below. The thinning experiment was carried out in the north-east Bahia, Brazil in sites with different productive capacities. The treatments corresponded to a reduction of 20, 35, 50% of stand basal area and an additional treatment of 35% removal plus pruning. We evaluated the growth in height before and after thinning, the dominant height × mean diameter ratio and the diameter distribution over time. There was no statistical difference in dominant height growth before and after thinning and neither between treatments, which allowed for the use of a single equation to represent dominant height growth. The average diameter and distribution of individuals across the diameter classes, on the other hand, were influenced by thinning weight. Our study reinforces that site index, as the mean dominant height at a reference age, would be used even after the application of thinning given that dominant height was not affected by this silvicultural treatment.

Keywords: Dominant height, thinning weight, diameter distribution, site index

INTRODUCTION

In 2015, industries linked to sectors of pulp and paper, wood panels, charcoal and timber consumed 194.4 million m^3 of logs from forest plantations in Brazil (IBA 2016). Of this, 16% were large-dimension saw logs. To meet the continuous demand for large logs, stands are managed under longer rotations compared with the common 7- to 6-year-rotation. These stands are subjected to thinning to promote more growing space for the remaining trees, increasing the production of usable wood (Campos & Leite 2013).

Tree growing space may define the yield of a forest stand. Yield depends on the optimal match of growing space and other factors such species, site productive capacity and thinning regime (Campos & Leite 2013). Thinning, when applied at adequate time and weight, may alter post-thinning growth trend. This change was shown to be more evident for diameter (Gorgens et al. 2007) but height was only slightly or not affected at all (Campos & Leite 2013, Weber et al. 2013).

Thinning is an important silvicultural operation when aiming at solid wood of bigger dimensions. Thinning can be applied from below by removing the suppressed low canopy trees, from above by removing some of the upper canopy trees, or in a combination of these two methods (Hawley 1949). The low-thinning is by far the most used across the world.

Dominant height is a well established proxy for site productive capacity and, hence, has been used in models to estimate growth and yield. Dominant height is the average height of the 100 highest trees per hectare (Burger 1976). Usually dominant trees are the largest trees in the stand (i.e. largest diameter at breast height (DBH) per stand) (Pothier & Savard 1998) and have crowns above the canopy level thus receiving direct sun light (Paiva et al. 2011).

Besides site productive capacity, dominant height of a stand is also positively correlated with basal area and mortality (Gómez-Tejero et al. 2009, Anyomi & Ruel 2015) and production

(Weber et al. 2013); because of that, it has been frequently used as a proxy for productive capacity in hypsometric (Tonini et al. 2001, Diéguez-Aranda et al. 2005, Gómez-Tejero et al. 2009) and volumetric (Pothier & Savard 1998, Mendonça et al. 2011, Leite & Andrade 2003) models and in the assessment of thinning (Schneider & Finger 1993, Weber et al. 2013).

In eucalypt stands, it is common to establish a fixed number of dominant trees per inventory plot at an initial age of about 3 years. The height and diameter of these threes are measured annually. For example, in a 500-m^2 plot, five dominant trees are marked. When a stand is thinned, the thinning effect may increase the growth dominant trees, which may result in deviation from the growth trend estimated by a guide curve applied for the classification of site productive capacity. In this case, the same guide-curve site classification procedure could not be used indistinctly for unthinned and thinned stands, even in the case of monoclonal stands with a same genotype. Therefore, the objective of this study was to assess whether height growth rhythm of dominant trees in eucalypt stands was affected by thinning from below. In addition we explored the effect of thinning weights on diameter distribution and dominant height × mean diameter relationship.

MATERIALS AND METHODS

Site and data description

We used data from a thinning experiment in *Eucalyptus* stands established in 1995 in the state of Bahia, north-eastern Brazil. The experiment was installed in three sites, A, B and C, capturing a gradient of productivity in which site C was the most productive followed by sites B and A. As the amount of annual rainfall (Table 1) follows the same gradient, productive capacity may have been limited by hydric stress. Water limitation has been shown to be the main constraint of *Eucalyptus* growth in Brazil (Stape et al. 2008, 2010).

Growth patterns for the height of dominant trees in each site is depicted in Figure 1. These curves were generated by fitting the Gompertz model (equation 1) relating total height of the dominant trees to stand age:

Table 1 Location of the experiments and amount of annual rainfall

Site	Municipality	Latitude (S)	Longitude (W)	Altitude (m)	Rainfall (mm year^{-1})
A	Inhambupe	11° 52'	38° 32'	285	900
B	Inhambupe	12° 03'	38° 28'	290	1100
C	Esplanada	11° 47'	37° 55'	150	1200

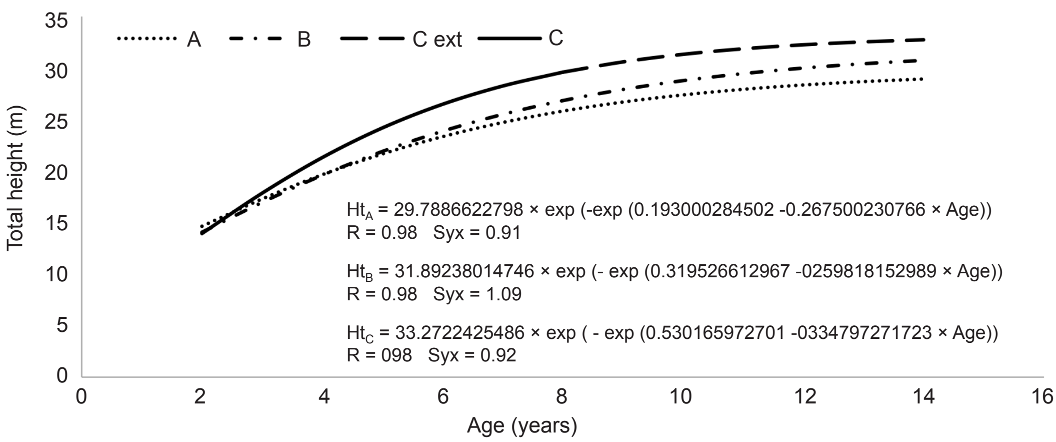

Figure 1 Growth pattern for total height of dominant trees (Ht) as function of age for the three study sites A, B and C; ext = extrapolated values, R = Pearson's correlation coefficient between observed and estimated heights, Syx = residual standard error; for site C, the inventory occurred up to the age of 7 years, therefore, from this point on the estimated values were extrapolated for comparison with the other sites

$$Y = \beta_0 \times e^{-(e^{(\beta_1 - \beta_2 \times Age)})} + \varepsilon \quad (1)$$

where Y = dominant height, e = exponential, β_0, β_1 and β_2 = parameters to be estimated, Age = stand age and ε = statistical error with normal distribution, zero mean and constant variance. These curves were statistically different when an identity test was applied (data not shown) for each pair of sites.

The experiment was implemented in a randomised block design with two blocks per site and two replicates of each treatment per block, totalling 48 plots. Each plot had an area of 2600 m^2, comprising 289 trees distributed in a 3 m × 3 m spacing. The treatments corresponded to different percentages of basal area removed in each thinning operation namely, 20 (T1), 35 (T2), 50 (T3) and 35 (T4). T4 differred from T2 trees in that the remaining trees in the former were also pruned to a height of 6.0 m at 27 months old. During thinning, the inferior trees were removed, i.e. the smallest ones in height and/or diameter, or the ones that were crooked, forked and/or broken.

Twelve measurements were carried out in which total height (Ht) of the first 15 trees, total height of five dominant trees (Hd) and DBH of all trees were recorded. The first thinning was performed at the age of 58 months and the second, 146 months old. Thinning schedule was determined according to the per cent entries method (Nogueira et al. 2001).

Modelling height growth of dominant trees

The Gompertz model (equation 1) was fitted to estimate the height of dominant trees before and after the first thinning. Data collected after the second thinning were not used as some dominant individuals were felled in this operation. Model fitting was performed in each treatment before and after thinning. We ran a model identity test with extra sum of squares F test (Table 2, Regazzi & Silva 2010, Campos & Leite 2013) to determine whether thinning treatments altered height growth rhythm (separate curves for the treatments vs one curve for each treatment pairs).

Considering that the data before and after thinning are not independent, we used the χ^2 non-parametric test (equation 2) (Regazzi & Silva 2010) to test whether thinning affected the growth rhythm of dominant trees (separate curves for before and after thinning tested against a single curve for both periods). The degrees of freedom of the χ^2 distribution was the difference in the number of parameters estimated by the full and reduced models. The test statistic was calculated using:

$$\chi^2_c = -n \times \text{In}\left(\frac{SSR_f}{SSR_r}\right) \quad (2)$$

where n = total number of observations, ln = natural logarithm and SSR_f and SSR_r = the sum of squared residuals of the full and reduced models respectively. Non-significance in these tests means no difference in growth rhythm due to thinning or to treatment.

Goodness-of-fit of the equations were assessed through Pearson's correlation coefficient between the estimated and observed values ($R_{Y\hat{Y}}$) (equation 3), residual standard error (S_{YX}) (equation 4) and through the analysis of residual plots. Formulas for these statistics are given below:

Table 2 Scheme of analysis of variance for the model identity test

Variation source	DF	SS	MS	F_c
Full model	PH	$\sum Y^2 - \sum\left(Y - \hat{Y}_C\right)^2$		
Reduced model	P	$\sum Y^2 - \sum\left(Y - \hat{Y}_r\right)^2$		
Reduction given to H_o	PH – P	SS full model – SS reduced model	SSH_0 / (PH – P)	(N – PH) × SSH_0 / (PH – P) × MSRes
Residual	N – PH	$\sum Y^2 - \left(\sum Y^2 - \sum(Y - \hat{Y}_C)^2\right)$	SSRes / (N – PH)	
Total	N	$\sum Y^2$		

DF = degrees of freedom, PH = number of parameter in the complete model, P = number of parameters in the reduced model, N = total number of observations, Y = total height of dominant trees, $\hat{Y}_C$ = estimated value for the complete model, $\hat{Y}_r$ = estimated value for the reduced model, SS = sum of squares, MS = mean square, Res = residual, c = complete model, r = reduced model and F_c = F calculated, H_0 = null hypothesis that the additional parameters of the complete model are not statistically different from 0

$$R_{Y\hat{Y}} = \frac{n-1\left(\sum_{i=1}^{n}\left(\hat{Y}_i - \hat{Y}_m\right)\left(Y_i - \bar{Y}\right)\right)}{\sqrt{n^{-1}\sum_{i=1}^{n}\left(\hat{Y}_i - \hat{Y}_m\right)^2\left(n^{-1}\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2\right)}} \quad (3)$$

$$S_{YX} = \sqrt{\frac{\sum_{j=1}^{n}(Y_1 - \hat{Y})^2}{n-p}} \quad (4)$$

where n = number of observations, $\hat{Y}_i$ = estimated value, $\hat{Y}_m$ = mean estimated value, Y_i = observed value, $\bar{Y}$ = mean observed value and p = number of estimated parameters.

Distribution of tree diameter

We graphically assessed the evolution of the observed diameter distributions considering all trees (dominant and non-dominant) and only the dominant trees. Diameter distribution histograms were built by merging all replicates (from different blocks and sites) but separating by age and thinning weight.

RESULTS

Modelling height growth of dominant trees

There was no significant difference between the full and reduced models for total height of dominant trees, which indicated that growth rhythm was not altered by thinning (Table 3). Frequency distributions of relative (per cent) errors indicated that all treatments had distribution close to normal, but slightly skewed towards positive values. This suggested that the models tended to overestimate the total height of dominant trees at older ages, especially in heavier thinning (Figure 2).

The model identity test for the equation of different treatments detected no statistical difference between the parameters for all contrasts (Table 4). As there was no significant difference between the coefficients of the equations fitted for each treatment and occasion (before and after thinning), a single equation (reduced model) could estimate the total height of dominant trees, independent of either the application or weight of thinning. This reduced model showed a correlation coefficient of 96% and residual standard error of 1.31 m. Growth pattern of height for dominant trees was not altered by any of the thinning weights and neither was it altered by the application of pruning in T4 (Figure 3).

Relationship between dominant height and mean diameter

Dominant height presented a narrower amplitude than mean diameter for all treatments at the age of 14 years (Figure 4). At this age, the range

Table 3 Goodness-of-fit statistics and model identity test for the Gompertz fitted equations for estimating the total height of dominant trees of *Eucalyptus* before and after thinning

Treatment (%)	Thinning	β_0	β_1	β_2	S_{YX}	$R_{Y\hat{Y}}$	p-value
20	Before	29.48626	0.60338	0.38181	0.99	0.96	0.10
	After	28.31828	0.69503	0.41984	1.53	0.78	
	Reduced model	28.35089	0.60280	0.40559	1.32	0.96	
35	Before	28.54943	0.63306	0.42052	1.07	0.95	0.21
	After	28.67597	0.63261	0.40118	1.64	0.77	
	Reduced model	28.56217	0.58476	0.40297	1.43	0.96	
50	Before	26.62332	0.69285	0.49055	1.05	0.95	0.62
	After	28.99986	0.65168	0.38694	1.46	0.82	
	Reduced model	28.87407	0.54181	0.38041	1.31	0.96	
35 + P	Before	27.05401	0.71727	0.48654	1.19	0.94	0.37
	After	28.45088	0.65060	0.40735	1.70	0.75	
	Reduced model	28.27305	0.59957	0.41369	1.50	0.95	

β = parameters estimated, S_{YX} = residual standard error, $R_{Y\hat{Y}}$ = Pearson's coefficient of correlation between estimated and observed values, p-value for the non-parametric χ^2 test in which values greater than 0.05 are considered non-significant, the percentage in treatment specification expresses the amount of basal area removed in thinning and P = pruning

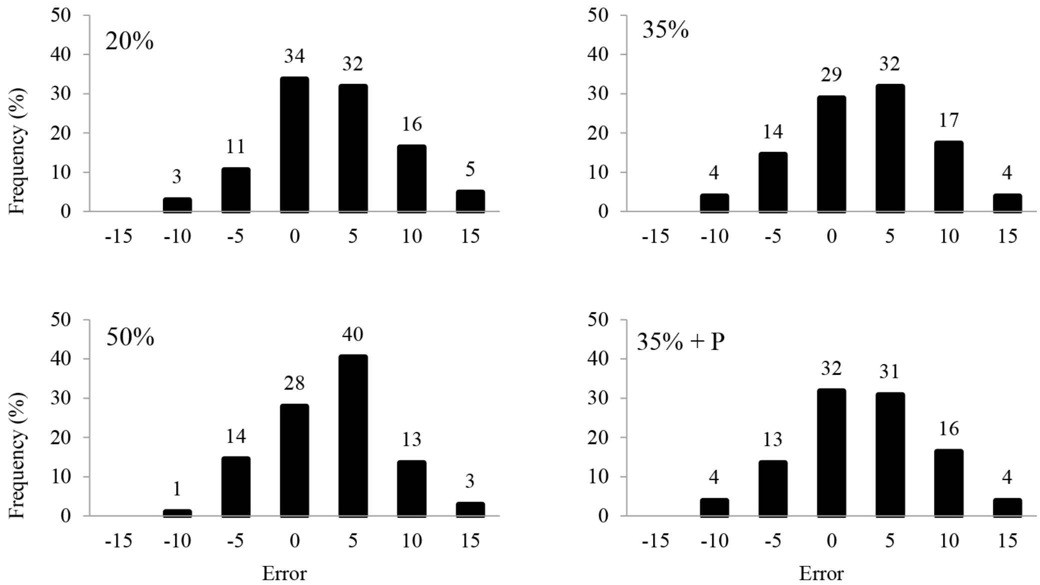

Figure 2 Distribution of per cent residuals between the observed and estimated total heights of dominant trees in *Eucalyptus* stands subjected to thinning; the percentage in treatment specification expresses the amount of basal area removed in thinning and P = pruning

Table 4 Goodness-of-fit statistics and model identity test for the Gompertz fitted equations for estimating the total height of dominant trees of *Eucalyptus* for four thinning weights

Contrast	β_0	β_1	β_2	S_{YX}	$R_{Y\hat{Y}}$	p-value
20 × 35%	28.46806	0.59832	0.40433	1.32	0.96	0.86
20 × 50%	28.62105	0.57601	0.39280	1.26	0.96	0.79
20 × 35% + P	28.29769	0.60954	0.41134	1.36	0.96	0.99
35 × 50%	28.74162	0.57129	0.39141	1.26	0.96	0.90
35 × 35% + P	28.41369	0.60516	0.41013	1.37	0.96	0.89
50 × 35% + P	28.56503	0.58187	0.39824	1.30	0.96	0.71
Reduced model	28.51577	0.59016	0.40133	1.31	0.96	-

β = parameter estimated, S_{YX} = residual standard error, $R_{Y\hat{Y}}$ = Pearson's coefficient of correlation between estimated and observed values, p-value for extra-sum of squares F test in which values greater than 0.05 are considered non-significant, the percentage in treatment specification expresses the amount of basal area removed in thinning and P = pruning

of variation in dominant height between the treatments was 8%. The greatest range of variation in dominant height considering the first and the last assessments, i.e. 2 and 14 years after planting respectively, was observed in the treatment with removal of 35% of basal area plus pruning (19.7 m), followed by the treatments 50, 35 and 20% with values of 19.2, 18.3 and 18.1 m respectively.

Mean diameter at the age of 14 years showed a 25% range of variation between treatments (Figure 3). The ranges of variation between the first and the last measurements were 17.3 cm for the treatment with 50% reduction of basal area and 16.8, 16.6 and 12.9 cm for the basal area reductions of 35 (+ pruning), 35 and 20% respectively.

Diameter distribution

Diameter distribution of all individuals (dominant and non-dominant) followed a normal trend (Figure 5). The diameter distribution of dominant individuals before the first thinning presented a leptokurtic shape in the early ages with mesokurtic trend in the following ages. However, before the first thinning, dominant trees were concentrated in fewer classes compared with

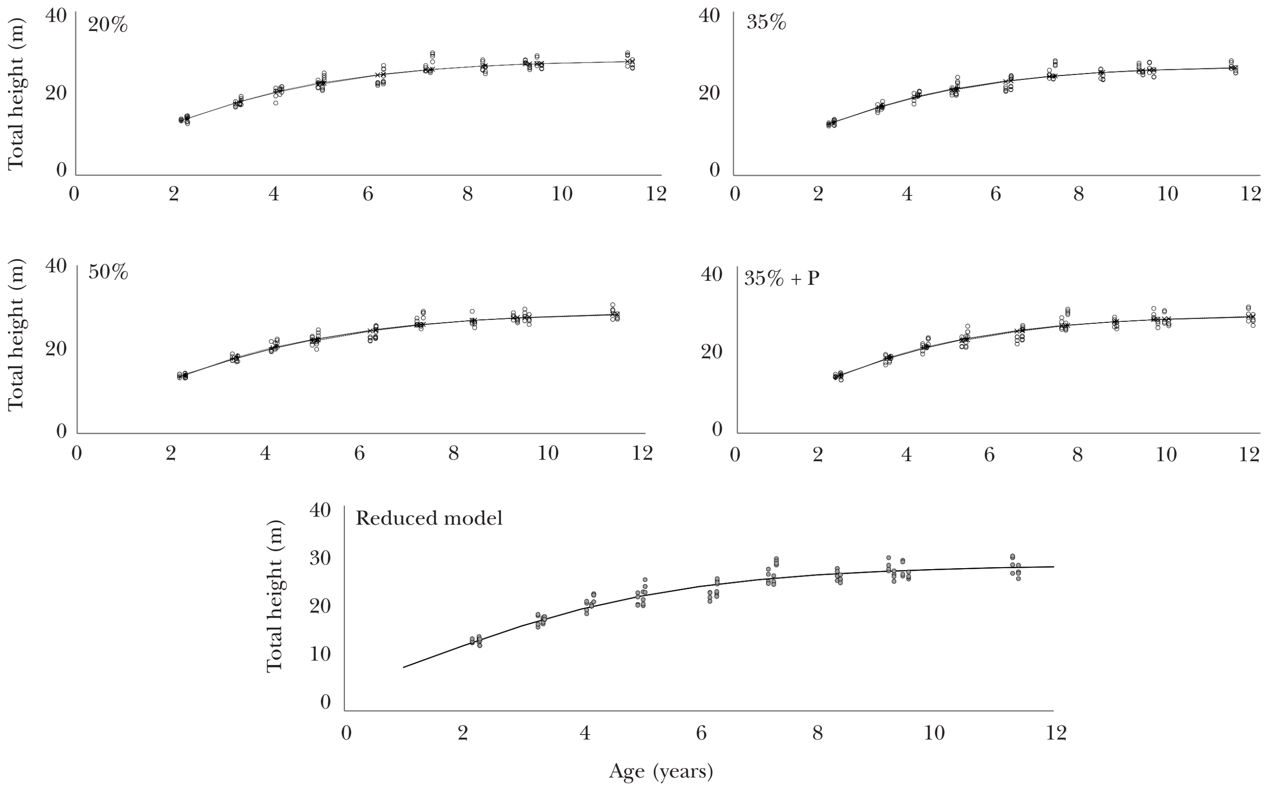

Figure 3 Observed and estimated total height of dominant trees of *Eucalyptus* subjected to thinning; o = observed height; ---+--- estimated height before the first thinning, ---×--- estimated height after the first thinning, — height estimated by the reduced model; the percentage in treatment specification expresses the amount of basal area removed in thinning and P = pruning

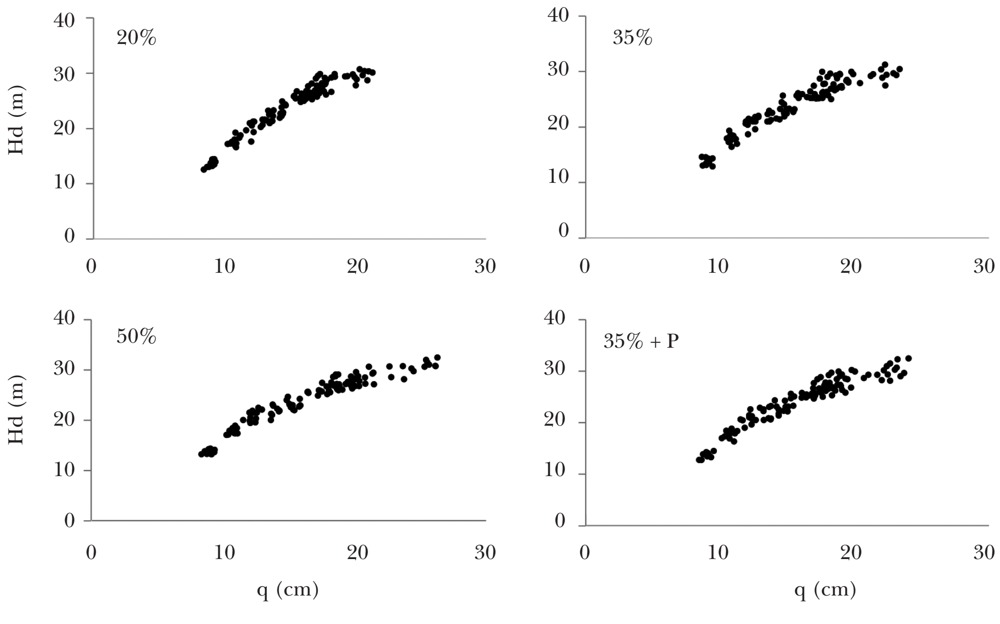

Figure 4 Relationship between dominant height (Hd) and mean diameter (q) of *Eucalyptus* submitted to thinning; the percentage in treatment specification expresses the amount of basal area removed in thinning and P = pruning

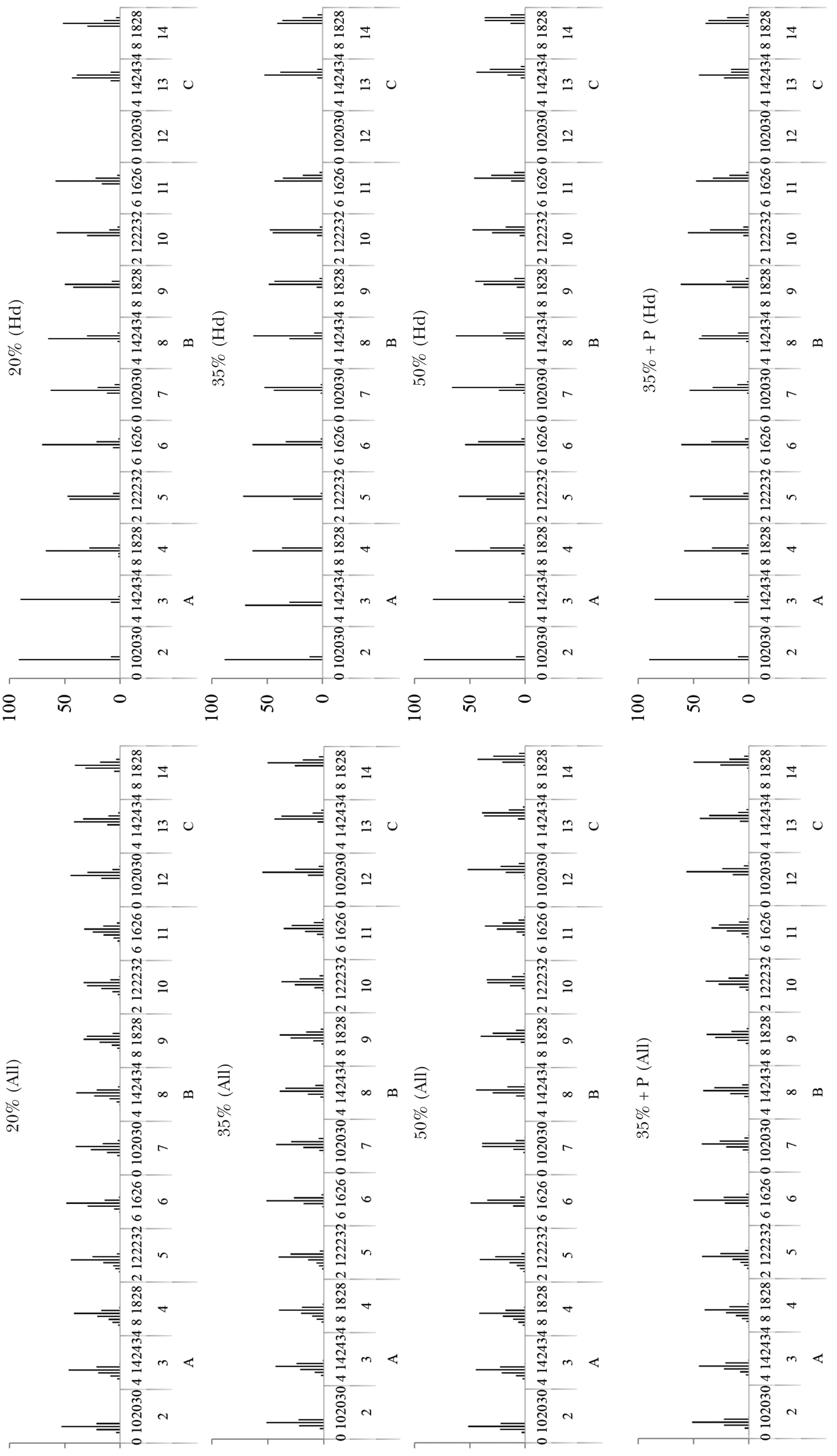

Figure 5 Diameter distribution of all the trees (All) and dominant trees (Hd) of *Eucalyptus* submitted to thinning; on the x-axis, the first subtitle refers to diameter class, the second subtitle refers to age (years) and the third, to thinning event where: A = before the first thinning, B = after the first thinning and C = after the second thinning; the percentage in treatment specification expresses the amount of basal area removed in thinning and P = pruning

other occasions. Preceding the first thinning, for all treatments, diameter classes of 14 and 16 cm presented the highest number of trees and dominant individuals respectively.

The effect of the first thinning on diameter distribution of all tress can be seen in Figure 4. At this point the treatment with 20% reduction of basal area presented higher number of diameter classes compared with the rest of the treatments. Similar to the previous phase, the distribution curves were leptokurtic and increasing left-skewness with age. The same trend was found for all treatments.

In the treatment with 35% reduction of basal area, the behaviour of the diameter distribution for all trees was similar between each other. Those with 50% of reduction in basal area showed lower number of classes before the second thinning. In this treatment, class 22 cm had the highest number of trees whereas in the other treatments, the 20-cm class had the greatest number of individuals.

After the first thinning, diameter distribution of dominant individuals was similar for all treatments. With age there was an increase in the number of classes which made the leptokurtic shape at the beginning of this phase move towards a mesokurtic trend. The treatment with 50% of basal area reduction presented the greatest number of trees in the 24-cm class (23–25 cm) whereas for the rest of the treatments the modal class was 22 cm (21–23 cm).

The diameter distribution of dominant individuals after applying the second thinning behaved similarly to the previous phase regarding the number of classes, but with a well-defined right-skewed asymmetry at the age of 14 years. At 14 years of age, the treatments with 50% of basal area presented the greatest number of trees in the class 26 cm whereas for the rest, the highest frequency was 24 cm. When considering all trees, modal class for dominant trees in the treatments with 50% of basal area reduction comprised bigger diameters (class centers of 26 and 28 cm) compared with the rest of the treatments where the modal class was 24 cm.

DISCUSSION

Modelling height growth of dominant trees

Regardless the weight, thinning with different weights did not change the growth rate of total height of dominant trees. These reinforce that thinning has little effect on height growth of dominant trees (Burger 1976). Thinning did not alter the dominant height growth rhythm in any of the treatments. This indicated that thinning was performed at the right timing, i.e. before the onset of competition among the trees for growth factors.

The results obtained in this research support important practical applications. The assessment of production capacity through the construction of site index curves whether by guide curve method (e.g. Pothier & Savard 1998) or through polymorphic site index models (e.g. Carmen et al 2001) could be performed in thinned stands when thinning was applied from below and before the onset of competition. This was also supported by other authors who found that dominant height did not depend on stand density (Burger 1976, Schneider & Finger 1993, Tonini et al. 2001).

There was no height growth stagnation for dominant trees which indicated that thinning was correctly applied. The thinning schedule in this experimental area was developed by Nogueira et al. (2001), Leite et al. (2005) and Dias et al. (2005). To determine the age at which thinning would be performed and the optimal time span between thinnings, Nogueira et al. (2001) applied the method of per cent entries designed by Garcia (1999). This method is based on growth dynamics and admission to successive diameter classes and allows for the determination of thinning schedule at least one year before the technical age of harvest.

The method of per cent entries is a biologically correct, consistent and appropriate technique not only to determine thinning schedule but also allows for simulation of thinning weight and age (Leite et al. 2005). The clutter model for predicting thinning is useful in the analysis of management alternatives such as determining the technical age of thinning of various site indices and thinning regimes (Dias et al. 2005). These results highlight the importance of adequate monitoring of the growth of trees and stands as well as the importance of scientific studies on silvicultural techniques such as thinning. This prevents or reduces the empiricism in obtaining and interpreting data, a fact that has been limiting the knowledge about the growth trends of post-thinning *Eucalyptus* stands (Leite et al. 2008).

The treatments in this study (basal area removal of 20, 35, 50 and 35% plus pruning) did not affect the growth rate of dominant trees. Similar results were obtained by Schneider and Finger (1993) and Weber et al. (2013). These authors found that thinning weights of 0, 25, 50 and 75% reduction in basal area did not influence the growth in total height of dominant individuals of *Pinus elliottii* and *Pinus taeda* respectively.

In addition, the application of thinning from below at the correct age resulted in higher economic return, as it provided maximum growth and production. This is explained by the fact that the remaining trees (dominant and codominant) possess better control of stomatal conductance, greater photosynthetic capacity, water and radiation interception, use efficiency and better nutritional status (Leite et al. 2005, Fernández et al. 2011, Campoe et al. 2013, Forrester 2013, Weber et al. 2013).

Relationship between dominant height and average diameter

In this experiment we found that there was no influence of thinning at different weights on total height growth of dominant trees, corroborating Schneider and Finger (1993), Leite et al. (2008) and Weber et al. (2013). On the other hand, diameter growth was significantly affected by the applied thinning weights. Mean diameter is influenced by density and can be used in defining thinning regimes, since it is directly related to the basal area of the stand and indicates the degree of occupation of the area (Gorgens et al. 2007, Campos & Leite 2013). Dominant diameter is also less sensitive to competition over time, compared with mean diameter (Leite et al. 2011).

Therefore, the use of the dominant height as an independent variable in hypsometric models is recommended mainly for different site productive capacities. The addition of this variable allows for the estimation of different heights for the same diameter depending on site quality (Campos et al. 1984, Leite et al. 2011).

Tree diameter distribution

Diameter distribution tended towards normality. At younger ages, distribution showed a leptokurtic shape which was asymmetry to the left. At older ages, distributions tended to be more platykurtic with a peak displacement towards the right which was clearly known to be promoted by the thinning from below (Burger 1976). Over time, diameter distribution in even-aged stands flattens down, moves towards the right, and there is reduction in the movement of trees towards successive diameter classes (Leite et al. 2005, Campos & Leite 2013).

Stands with 50% removal of basal area, i.e. the lowest density after thinning, had mean diameter 5 to 6% greater than treatments with 35% basal area removal, with and without pruning respectively, and 12% greater than the treatment with 20% basal area removal. This reinforced that diameter is very sensitive to stand density (Leite et al. 2011, Campos & Leite 2013).

CONCLUSIONS

Thinning from below with reductions of 25, 35 and 50% of basal area, applied at the age of maximum mean annual increment had no effect on growth rates of height of dominant trees in *Eucalyptus* stands. On the other hand, mean diameter and the diameter distribution were affected by thinning. The knowledge and understanding of growth dynamics of even-aged stands in different productive capacities sites allow for the analysis and choice of the most appropriate management alternatives for each site.

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