MANAGEMENT OF INDIVIDUAL TREE DIAMETER GROWTH AND IMPLICATIONS FOR PRUNING FOR BRAZILIAN *Eucalyptus grandis* Hill ex Maiden

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Recebido para publicação: 07/06/2006 – Aceito para publicação: 25/07/2006

Abstract

In the present work a thinning program and a model describing dynamic of crown base recession for *Eucalyptus grandis* was established on an individual tree basis. Therefore, 485 trees were measured on temporary plots in forests of the companies Klabin Riocell (Guaíba), Todeschini (Cachoeira do Sul), the Federal University of Santa Maria and Aracruz Company, located in Rio Grande do Sul, Espirito Santo and Bahia, Brazil. A straight relationship between crown width and diameter at breast height (DBH) was found by using regression analysis. The equation obtained was crown width = $e^{0.504+0.0307*\ DBH}$, with a coefficient of determination of 0.78 and a standard error of 0.034. With this equation the standing space of the individual trees was calculated over the whole rotation period, taking into account a crown cover of 70 %. Therefore the number of trees which can be grown on a hectare was derived for different variants of management systems aiming to produce eucalypt sawlogs in short rotation periods. Beside this a multivariate model describing height of crown base as a function of DBH and total height was found. Based upon this model the dynamics of crown base recession for different site qualities and thinning regimes are described, giving advice for time and intensity of green pruning.
Keywords: Diameter growth; pruning; thinning; *Eucalyptus grandis*; growth model.

Resumo

Manejo do crescimento em diâmetro da árvore individual e o impacto para a poda de Eucalyptus grandis no Brasil. No presente estudo, foi desenvolvido um programa de desbaste e um modelo para a descrição da dinâmica da base da copa. Para esse fim, 485 árvores foram medidas em parcelas temporárias das empresas Klabin Riocell (Guaíba, hoje Aracruz), Todeschini (Cachoeira do Sul), Universidade Federal de Santa Maria (RS) e Aracruz Celulose (Espirito Santo e Bahia). Foi encontrada uma correlação linear entre a largura da copa e o diâmetro à altura do peito (DBH), usando-se a metodologia da análise de regressão. A equação obtida foi largura da copa = $e^{0.504+0.0307*\ DBH}$, com um coeficiente de determinação de 0.78 e um erro padrão de 0.034. Com esse modelo, foi calculado o espaço da árvore individual necessário para alcançar um determinado crescimento em diâmetro durante todo o ciclo de rotação, considerando uma cobertura do dossel média de 70%. Assim, o número de árvores por hectare em diferentes estágios de desenvolvimento foi calculado para diferentes sistemas de manejo com o objetivo de produzir madeira para serraria em ciclos de rotações curtas. Também foi obtido um modelo multivariado descrevendo a altura da base da copa viva em função das variáveis diâmetro à altura do peito (DBH) e altura total. Com base nesses modelos, a dinâmica na inserção da copa viva para diferentes sistemas de manejo em sítios de diferentes qualidades pode ser calculado, possibilitando assim a determinação do ponto ótimo e da intensidade da poda.
Palavras-chave: Crescimento em diâmetro; poda; desbaste; modelo de crescimento; *Eucalyptus grandis*.

INTRODUCTION

Plantation forestry is a very important part of the Brazilian forestry sector. Representing only 1.3 % of the total forest area of the country, it contributes to more than 60% of the wood production. From 7 million ha of plantation forests existing in Brazil, almost 5 million ha are considered as industrial plantations with the aim of producing pulpwood, mainly from the genus *Eucalyptus,* with approximately 3 million ha, and *Pinus* (BROWN, 1997).

The growing conditions for *Eucalyptus grandis Hill* ex Maiden in Brazil in general are very good. Best sites with high productive clones often show an average annual increment of 60 to 80 m³/ha/yr at the age of 6 years, in some exceptional cases exceeding 100 m³/ha/yr. Management methods for *Eucalyptus* generally are based on initial spacings of 3 x 1.5 m to 3 x 3 m after a deep soil preparation (40 cm) and fertilizing. Depending on site quality a second fertilizing is conducted at the age of 3 to 4 years. For the cellulose production in general no thinnings are necessary, harvesting age varies between 5, 7 and on poorer sites about 10 years. At this age the trees show up heights of 26 to 35 m and stand densities of 1000 trees/ha can be observed.

The goal of high quality timber production with eucalypt is rarely mentioned in Brazilian forest management literature. To date, in Brazil the wood of eucalypt plantations has mainly been used for the production of cellulose, fuelwood and charcoal. This generally requires a management regime that is based on maximizing timber volume. However, within the last few years, a market sector using *Eucalyptus* in the furniture industry for panels and plywood has been established in Brazil and elsewhere.

The reason for this development can be seen in various factors (DONNELLY *et al*., 2003, FLYNN; SHIELD, 1999; LIMA *et al*., 1998):

- temporarily global oversupply of eucalipt pulp and pulpwood, leading to low prices and returns of investment below the expected;
- decreasing availability of hardwood timber from native forests of Asia, Africa and South America due to over-exploitation and better environmental protection of native species, and at the same time an increasing demand for wood of higher quality;
- environmental concerns for the use of wood products of tropical rainforests and a movement towards the use of timber of certified and sustainable managed forests;
- advances in genetics and innovative techniques for processing eucalypts, solving most of the problems of drying and splitting.

The most important parameters that can be influenced by silvicultural management strategies for high quality timber production are dimension (diameter) and internal knottiness (GERRAND *et al*., 1997; HAWLEY; SMITH, 1972). Silvicultural management regimes aiming for high quality timber production in general lead to longer rotation periods. An alternative could be a strategy where trees with outstanding characteristics in terms of growth and quality are pre-selected and thinned until the end of the rotation period (ABETZ, 1975; SELING *et al*., 2001). Thus emphasis is changed to the individual tree. Such a thinning program consequently requires individual tree parameters to be used for growth optimisation.

New management approaches for sawlog production in Brazil try to use the high diameter increment potential of *Eucalyptus grandis* of 4 to 7 cm per year in the first 3 years, with the aim of producing target diameters of 35 to 40 cm in short rotations of 10 years. Such a high diameter growth can be achieved by planting at sites of good quality in wider initial spacings of 4 x 4 to 5 x 5 m and by thinning as soon as the canopy closes. On good sites and with spacings of 3 x 1.5 to 3 x 3 m this occurs at the age of 9 to 15 months. At this time the lower branches already begin to die and with an average height increment of 5 to 6 m/yr this process accelerates in the following years.

Natural pruning of *Eucalyptus grandis* is discussed controversially in literature. While Lamprecht (1986) and Mangieri; Dimitri (1961) state that eucalypts show a good self-pruning, newer studies from Australia and South Africa strongly recommend pruning for eucalypt sawlog production (BREDENKAMP *et al*., 1980; HENSKENS *et al*., 2001; PINKARD; BEADLE, 1998a; PINKARD; BEADLE, 1998b; SCHÖNAU, 2002). Especially when managed under a fast growing regime *Eucalyptus* tends to include dead branches partly into the bole. Thus, a knotty core of bigger dimension is sustained reducing the value of the wood. With more growing space the crown develops more vigorous, and the branches stay alive for a longer period. Like already shown for *Picea*, *Populus* and *Quercus* (DELEUZE *et al.*, 1996; NELSON *et al.*, 1981; NUTTO, 1999), there is a strong relationship between branch length and branch diameter. This relationship could also be shown for *Eucalyptus globulus* (HENSKENS *et al.*, 2001, NUTTO; TOUZA, 2004).

Therefore, if the aim is to produce more clearwood, it is recommendable to conduct an artificial pruning (MEDHURST *et al.*, 2001). Pruning of dead branches, however, leads to pockets in the stem wood which are filled with gum, resulting in checks and unwished disturbances in the fibre flow in the inner part of the stem (WARDLAW; NEILSEN, 1999; STACKPOLE, 2001).

Management tools based on parameters collected at stand level, such as relative spacing (HART, 1928) or stand density management diagrams according to Drew; Flewelling (1979) represent only a mean value of tree collectives with more or less variance. Decision supporting tools developed from individual tree models, however, allow the prediction of growth of the individual tree as well as an average stand development.

An important relationship based on individual tree parameters used in many growth studies is the relation between crown size and tree diameter. In 1964 Curtin tested the relationship between structural crown parameters and tree diameter for *Eucalyptus obliqua*. Spathelf *et al.* (2000) analysed the impact of crown size and diameter at breast height for a small sample size of *Eucalyptus grandis*, where crown width served as a driving variable for diameter growth conduction. On the other hand branch development and crown expansion are strongly influencing self-pruning dynamics (SELING *et al.*, 2001).

Objectives

The presented study aims to point out the interactions between diameter and height growth and the self-pruning dynamics of *Eucalyptus* in order to evaluate different management regimes according to their effectivity for high value wood production.

The specific objectives of this study are to.

- establish an individual tree diameter growth model for *Eucalyptus grandis* based on the relationship between diameter at breast height (1.3m) and crown width;
- analyse the effect of Site Index on the maximum radial increment an individual *Eucalyptus grandis* tree can achieve;
- establish an individual tree model for *Eucalyptus grandis* that explains the crown base recession dynamics, based on height of crown base, diameter at breast height and crown width.

MATERIAL AND METHODS

Experimental area and material

The study areas are located in the forest districts of

- Klabin Riocell S.A. (geographical co-ordinates: between 30°09' and 30°23' S and 51°09' and 58°06' W, with an slightly to heavily undulated relief);
- Todeschini S.A. (geographical co-ordinates of 30° to 31° S and 52° to 53° W (slightly undulated relief);
- Aracruz company in the states of Espirito Santo and Bahia (located between the parallels of 19°40' to 17°47' S and 40°2' and 35°35' West, plain) and
- in sample plots of the University of Santa Maria (located between the parallels of 29°43' to 29°55' S and 53°42 to 53°48' W).

The height above sea level varies between 0 to 450 m. Climate in the study region is subtropical humid in the southern part of Brazil and tropical humid in Espirito Santo and Bahia, according to the climatic classification of Köppen (MORENO 1961). This means the absence of long lasting periods with water deficit but with the occurrence of several frosts in winter (May-August) in southern Brazil. Mean annual precipitation is 1322 mm and mean annual temperature 19.3 ºC. In the states of Espirito Santo and Bahia the climatic conditions are quite different. In the southern part of the Aracruz forests, mean annual precipitation is 1281 mm and mean annual temperature 23.6°C, with a dryer season from June to August. In Bahia, mean annual precipitation of 1394 mm is distributed more equally during the year and mean annual temperature is 24°C.

The soils in the study area are dominated by latosols (humic acid deeply weathered soils) in the south and podsols with a sandy loamy structure at Espirito Santo and Bahia sites (EMBRAPA, 2000). A limiting factor for these soils is their poor exchangeable nutrient stock. The former native vegetation at the southern Brazilian study site was a semi-deciduous forest in the Central Depression and oceanic influenced pioneer formations in the coastal area. At the coastal part of Espirito Santo the former native vegetation was the so called 'Mata Atlantica', a strip of tropical rain forest that formerly reached from the Amazon Region down to the state of Parana. Today only 2 % of these native forests are left.

In table 1 some characteristics of the sampled stands of *Eucalyptus grandis* are documented.

Table 1. Characteristics of the sampled stands.
Tabela 1. Características dos talhões de eucalipto usados neste estudo.

Plot	Site index	Initial spacing (m x m)	Age (years)	DBH (cm)	$ir_{1,3}$ (cm)	Dominant height (m)	Crown width (m)
Riocell 1	28	3 x 2	3	12.9	2.15	15.0	2.6
Riocell 2	24	1.8 x 3	10	24.1	1.21	32.4	3.3
Riocell 3	31	3 x 2	12	32.3	1.34	36.5	4.8
Riocell 4	30	3 x 2	12	32.5	1.35	35.6	4.5
Riocell 5	28[1]	3 x 1.8	16	41.2	1.29	41.2	5.1
Riocell 6	31[1]	2.7 x 2	19	49.4	1.30	47.5	8.4
Todesflor 1	29	3.5 x 1.5	9	25.4	1.41	31.6	3.7
Todesflor 2	20[1]	3.5 x 1.5	20	27.5	0.69	31.3	3.4
Todesflor 3	20[1]	3.5 x 1.5	20	26.9	0.67	30.3	4.2
Todesflor 4	30	3.5 x 1.5	9	25.6	1.42	33.1	4.3
UFSM 1*	26	3 x 2	9	22.9	1.27	27.7	3.9
UFSM 2	25	3 x 2	9	22.0	1.22	26.9	3.3
Aracruz 1	26[1]	3x3	21	35.6	0.9	36.9	5.1
Aracruz 2	32	3x3	1.5	9.1	3.05	11.0	2.8

[1] Extrapolation of age (see Finger 1991); $ir_{1.3}$: mean annual radial increment at breast height. *UFSM: Sample plots of the Federal University of Santa Maria.

[1] Extrapolação da idade (segundo Finger 1991); $ir_{1.3}$: incremento radial médio por ano a altura do peito. *UFSM: Parcelas experimentais da Universidade Federal de Santa Maria-RS.

Working hypothesis

As stated in the introduction it is assumed that diameter at breast height is linearly correlated with crown dimension. Consequently, the first working hypothesis is:

$$cw = f\,(DBH) \qquad (1)$$

where: cw = crown diameter; DBH = diameter at breast height.

Crown diameter is a substitute for a tree's standing space (Dawkins 1963). Therefore the crown expansion serves as driving variable for diameter growth control.

The second working hypothesis expresses the limitation of maximum diameter increment by site productivity.

$$id_{max} = f\,(SI) \qquad (2)$$

where: id_{max} = maximum radial increment; SI = site index, dominant height at the age of 7 years (FINGER, 1991).

Living crown recession is influenced by two factors: crown size and height growth. In the first hypothesis it was assumed that tree diameter is a good estimator for crown size. Larger crowns mean more growing space available for the individual tree, that means lower competition and shading intensity. Height growth on the other hand is influencing intra and inter-tree shading. At good sites with accelerated height growth canopy closure with its self-shading effect occurs earlier, that means a higher competition factor can be expected. Consequently also crown base recession will be affected.

Therefore the following third working hypothesis is established:

$$hcb = f\,(dbh, h) \qquad (3)$$

where: hcb = height of crown base; h = total tree height.

Sampling and measurements

The database comprises measurements in stands on different sites and at different development stages. Moreover, trees which only suffered little competition were sampled to establish the maximum radial increment – site relationship.

Crown expansion, radial growth and dynamic of self-pruning were analysed by measuring temporary sample plots with 35 trees each. Preliminary studies on the variation of the main tree characteristics showed that this number of trees is sufficient to conduct statistical analyses with an error of 5% of probability of the parameters used in the study. Only the sampling of several neighbouring trees together allowed the ability to estimate the effect of competition on tree characteristics. The first tree of every sample plot was selected using a distance and an angle generated randomly. From this tree, which received the co-ordinates (0/0), the other 34 trees were localized measuring the deviation from north and the distance. On every tree diameter at breast height, total height, height of crown base, height of the first dead branch and crown projection area were measured. Branches derived from epicormics were not considered for height measurements.

Crown projection was estimated by measuring eight crown radii. This represents the best compromise between accuracy and efficiency when measuring trees with asymmetric crowns (RÖHLE, 1986). With this data tree distribution maps with the respective crown projection areas were generated. Average crown closure was calculated with a digitiser using a sub-sample of the 35 trees, which were delimited on the stem distribution maps. The percentage of crown cover is of great importance and has to be considered in distant-dependent growth models (DAWKINS, 1963; NUTTO, 1999; SPIECKER, 1991).

Branch length (total length including curvatures) and branch diameter (measured at the branch base) data were collected on a sub-sample of 150 branches between 1 and 4 cm of branch diameter.

Data processing

All data processing was conducted using the statistical package Statistical Analysis System (SAS, 1987; SAS, 1988; SAS, 1992). The procedure of 'stepwise' was used to select the independent variables of all regression models. To identify the best model the adjusted coefficient of determination (R^2_{adj}), the standard error (S_{yx}) as well as residual analysis was used. To study the relationship between two variables the Pearson product-moment correlation analysis was used (COHEN; COHEN, 1975).

RESULTS

Diameter increment model

Table 2 shows the results of correlation analysis of diameter at breast height and crown parameters. All variables are significant at a level of 1 %.

Table 2. Correlation coefficients matrix after PEARSON, Prob > |R| with H_0: Rh_0=0 / N=420 (SAS 1987).
Tabela 2. Matriz de coeficientes de correlação de PEARSON, Prob > |R| com H_0: Rh_0=0 / N=420 (SAS 1987).

	Crown projection area	**Crown width**	**Diameter at breast height**
Crown projection area	1		
Crown width	0.97	1	
Diameter at breast height	0.80	0.87	1

Regression analysis with crown width as dependent variable and diameter at breast height as independent variable showed that crown width significantly increases with increasing diameter at breast height, but it was found increasing variance of the crown width for higher dbh-values, which indicated heteroscedasticity. A logarithmic transformation equalized the variances of crown width. The model is represented in the following form (see Figure 1).

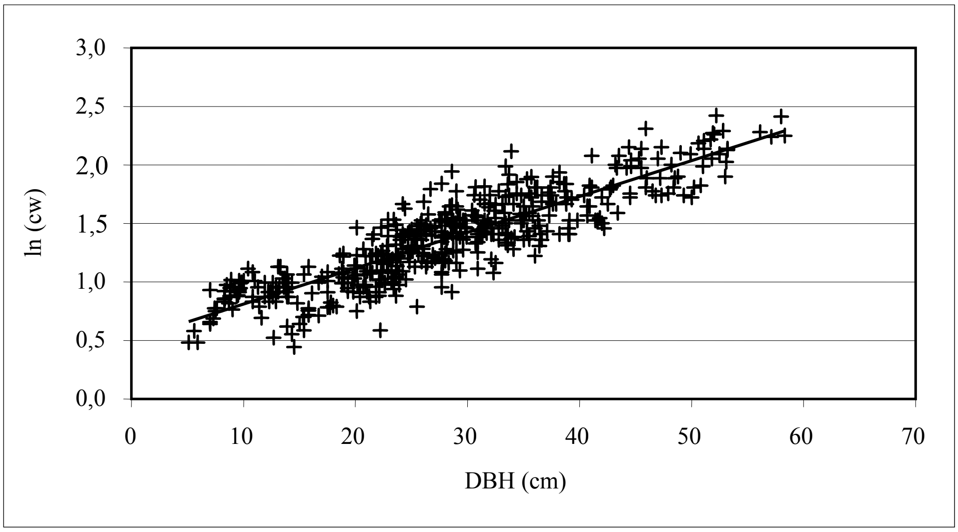

Figure 1. Model of crown width (cw) as a function of diameter at breast height (DBH).
Figura 1. Modelo da largura da copa (cw) em função do diâmetro a altura do peito (DBH).

The fitted model equation is

$$cw\ (m) = e^{0.504+0.0307*DBH(cm)}$$
$$(r^2 = 0.78,\ F = 1709)$$

Site index model for estimating maximum radial increment

According to the model established diameter growth can be controlled by crown expansion, which ultimately is a function of competition regulation. Moreover, on productive sites standing space can be occupied more rapidly than on poor sites because of a major potential of crown expansion (SPATHELF *et al.* 2000). Thus, not only height growth but also diameter growth is limited by site productivity. In figure 2 the relationship between maximum diameter increment and site index was modeled with a simple linear regression. It can be shown that sites with a higher productivity reveal, such as with height growth, a higher capacity of crown expansion. The question is if with ongoing age high diameter increments of 6 cm can be maintained. These values were only measured in younger stands up to 3.5 years. It seems to be realistic to assume maximum diameter increments of 4 cm per year at sites of upper quality. This is endorsed by the measurements of several trees at the age of 13 years where accidental circumstances led to more growing space.

The regression equation is:

$$id_{max}\ (cm/y) = 0.3397 * SI - 4.6456$$
$$(r^2 = 0.89,\ F = 113)$$

Model for estimating dynamics of living crown base recession

The correlation coefficients of crown base, diameter at breast height and total height (Table 3) indicate that a model based on these parameters probably shows a statistical relationship and is able to explain a good part of the occurring variation in height of crown base. The equation is:

$$\text{height of crown base (m)} = -5.12 - 0.407*DBH\ (cm) + 1.193*\text{height (m)}$$
$$(R^2 = 0.87,\ F = 1626)$$

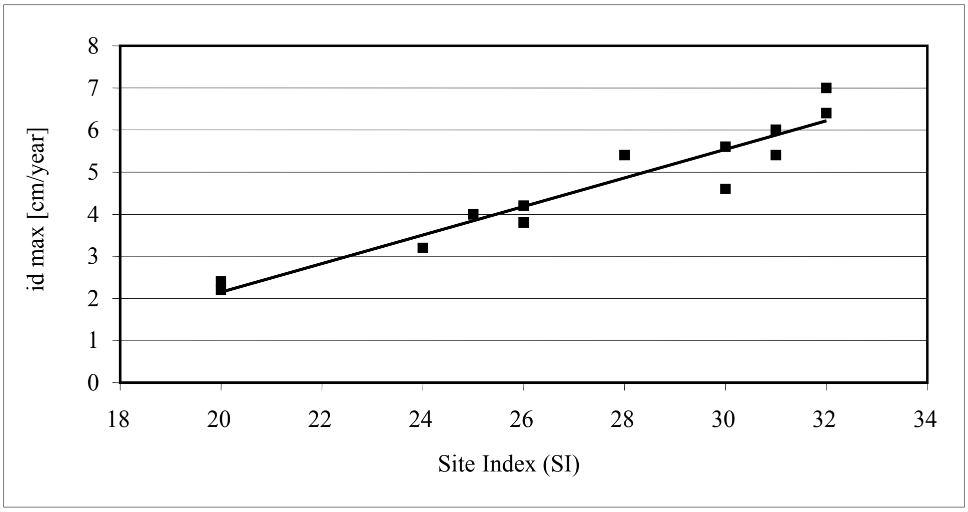

Figure 2. Maximum diameter increment (average of the 5 biggest trees found in each of the 14 sample plots) as a function of site index (dominant height at the age of 7 years, yield tables of Finger (1991)).
Figura 2. Incremento em diâmetro máximo (média das cinco árvores mais grossas encontradas em cada uma das 14 parcelas) como uma função de índice do sítio (altura dominate na idade de 7 anos, tabelas de produção de Finger (1991)).

It can be noted that for the best fit of the model the intercept is negative, which from a biological point of view makes no sense, since a crown base can never be negative. The t-value of the intercept in the model is highly significant and no negative values occur if the model is applied in the limits of the the data base of the study.

Table 3. Correlation coefficients matrix after PEARSON, Prob > |R| with H_0: $Rh_0=0$ / N=420. All values are significant at a level of 0.0001 (SAS, 1988).
Tabela 3. Matriz de coeficientes de correlação de PEARSON, Prob > |R| com H_0: $Rh_0=0$ / N=420. Os valores são significativos a um nível de 0.0001 (SAS, 1988).

	Crown base	**DBH**	**Total height**
Crown base	1		
Diameter at breast height	0.73	1	
Total height	0.91	0.91	1

The residuals were tested with χ^2 estimator (SAS, 1988) which showed that a normal distribution can be assumed for the multivariate model. The model leads to the result, that with increasing total height the height of crown base also increases. On the other hand diameter at breast height shows a negative effect on crown base recession in the model. That means that released trees with larger crowns and therefore bigger diameters have a retarded self-pruning.

Observing height of lowest dead branch and its correlation to tree height and height of crown base, only a weak and non-significant correlation was found. This indicates that with the analysed material and the thinning systems applied on it, self-pruning of Brazilian *Eucalyptus grandis* is insufficient for producing high quantities of clear wood. There is only a slight trend that with increasing total height the height of lowest dead branch also increases. Therefore, for *Eucalyptus* solidwood production in short rotations of 10 to 15 years, artificial pruning is necessary for improving the dimension of the knot-free core and internal wood quality.

Wide initial spacings offer more growing space for the individual tree, crowns grow for a longer period without competition and branches get longer and bigger. The bigger the branches, the bigger the disturbance of the internal wood structure and the higher the risk of decays in the stemwood.

$$\text{branch length (m)} = 1.38 * \text{branch diameter (cm)} + 0.204$$
$$(r^2 = 0.76, F = 449)$$

There is a straight relationship between branch length and branch diameter (Figure 3).

With the help of this equation it can be estimated that critical branch diameters of 3 cm will be reached with a branch length of 4.5 m. Assuming that branch angle to vertical stem axis is 90°, one can estimate that a distance between planting rows of 9 m would assure that crown contact and therefore competition occurs early enough to avoid branch length over 4.5 m. If a branch angle of 45° is assumed the vertical distance between the trees at maximum should be 6.2 m.

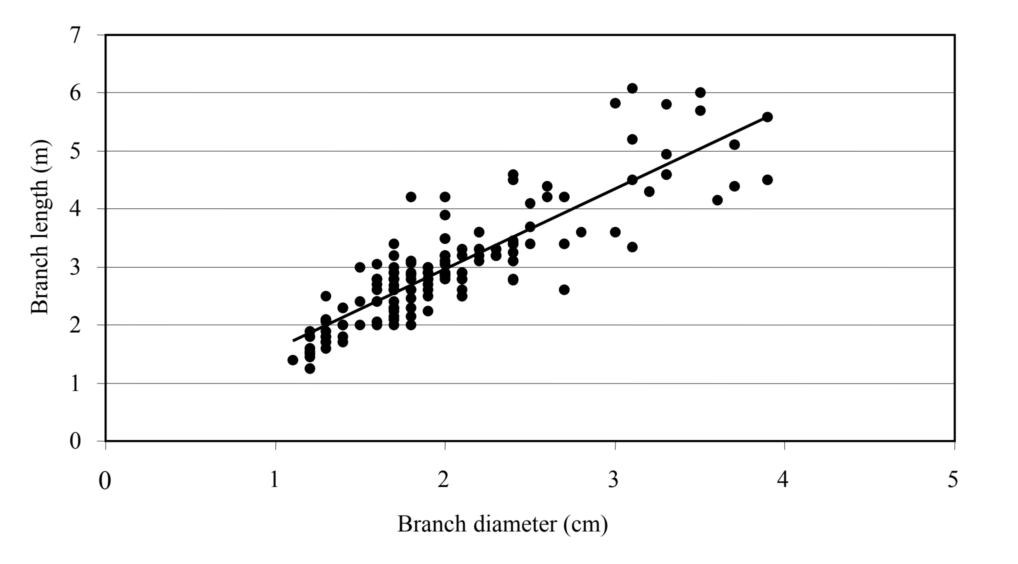

Figure 3. Relationship between branch length and branch diameter (*Eucalyptus grandis*, branches from 10 trees, n= 150).

Figura 3. Correlação entre o comprimento do galho e o diâmetro do galho (*Eucalyptus grandis*, galhos de 10 árvores, n= 150).

Decision tools for estimating diameter growth

For *Eucalyptus grandis* a crown cover percentage of 70 % of the available growing space was found. This value represents the average of all 14 plots measured and varied between 65 and 75 %. With the equation crown width = $e^{0.504+0.0307*DBH}$ it is possible to calculate the vital space needed by a future crop tree to get a determined dimension. Knowing this, the number of eucalypts per ha can be calculated, taking into account that only part of the total available area is covered by canopy.

Table 4. Estimated number of future crop trees per hectare with a given target diameter with the help of the crown width model (canopy density factor = 0.7).

Tabela 4. Número de “árvores futuras” por hectare com um certo dap desejado, estimadas com a ajuda do modelo da largura da copa (fator de cobertura do dossel = 0.7).

Target DBH (cm)	Crown width (m)	N^o. of trees/ha
40	5.65	279
45	6.59	205
50	7.68	151
55	8.96	111
60	10.44	82

Another important observation which can be made regarding table 4 is that with increasing target diameter the number of trees growing per hectare is decreasing significantly. An early selection of future crop trees for selective thinning and pruning reduces the number of trees that have to be removed in the first and mostly pre-commercial thinnings and also reduces the number of trees where cost intensive pruning has to be done.

Table 5. Reduction of stems/ha calculated for a given diameter increment and the corresponding crown width (planting spacement 3 x 2.75 m = 1200 trees/ha, canopy density factor = 0.7).

Tabela 5. Redução do número das árvores / ha calculado para um crescimento em diâmetro pré-definido com a respetiva largura da copa (espaçamento inicial 3 x 2.75 m = 1200 árvores/ha, fator da cobertura do dossel = 0.7).

Age	Site of lower quality, average annual diameter increment (id) = 2.8 cm/year				Site of higher quality, average annual diameter increment (id) = 3.6 cm/year			
	id (cm/yr)	DBH (cm)	cw (m)	N/ha	id (cm/yr)	DBH (cm)	cw (m)	N/ha
1	5	5	1.9	1200	6	6	2.0	1200
3	3.5	12	2.4	1200	5	16	2.7	1200
5	3	18	2.9	1078	4	24	3.5	746
7	3	24	3.5	746	3.7	31.5	4.4	470
9	2.8	29.5	4.1	532	3.2	38	5.3	316
11	2.5	34.5	4.8	391	3	44	6.4	218
13	2	38.5	5.4	306	2.8	49.5	7.6	156
15	1.5	41.5	5.9	255	2.5	54.5	8.8	115

cw: crown width (m) for a crown cover of 70 %; DBH: diameter at breast height (cm); N: maximum number of eucalypts/ha (with an average crown coverage of 70 %).

cw: largura da copa (m) para uma cobertura do dossel de 70%; DBH: diâmetro a altura do peito (cm); N: número máximo de eucaliptos/ha (com uma cobertura do dossel média de 70%)

In table 5 potential growing situations for *Eucalyptus grandis* for two different site qualities are shown. With an initial spacing of 3 x 2.75 m (1200 trees/ha) canopy closure occurs in both cases at the age of 3 years. Crown expansion at the site of lower quality during this time is less compared with the site of higher quality. Therefore the ability of the tree to produce more assimilates is restricted, leading consequently to lower diameter increment during the whole rotation period. At cutting age the trees therefore reach different diameters and show different average diameter increments for the same rotation period.

The analysed material did not allow to conduct retrospective analysis of tree rings because annuality of growth could not be proven. Without any data it seems to be reasonable to calculate with decreasing diameter increment with age (Table 5).

In figure 4 diameter increment and tree number reduction for two thinning strategies for eucalypt sawlog production (target diameter 45 cm) is shown and compared with a conventional management regime. In comparison to traditional pulpwood management (FINGER, 1991) with denser initial spacing and no thinnings, diameter increment can be maintained at a higher level.

Observing development of basal area and stand volume for the 3 variants (Figure 5) there is evidence, that the thinning regime leads to superior values during the first 8 years of stand rotation. This is due to the very high diameter increment in the thinning variants which is able to compensate lower number of stems per hectare and higher stem taper. Obviously it seems to be possible to concentrate stand increment on a few number of trees per hectare in the first 8 to 10 years. After this time the continuous reduction of tree number results in a decreasing stand volume, because height and diameter growth decrease at older ages.

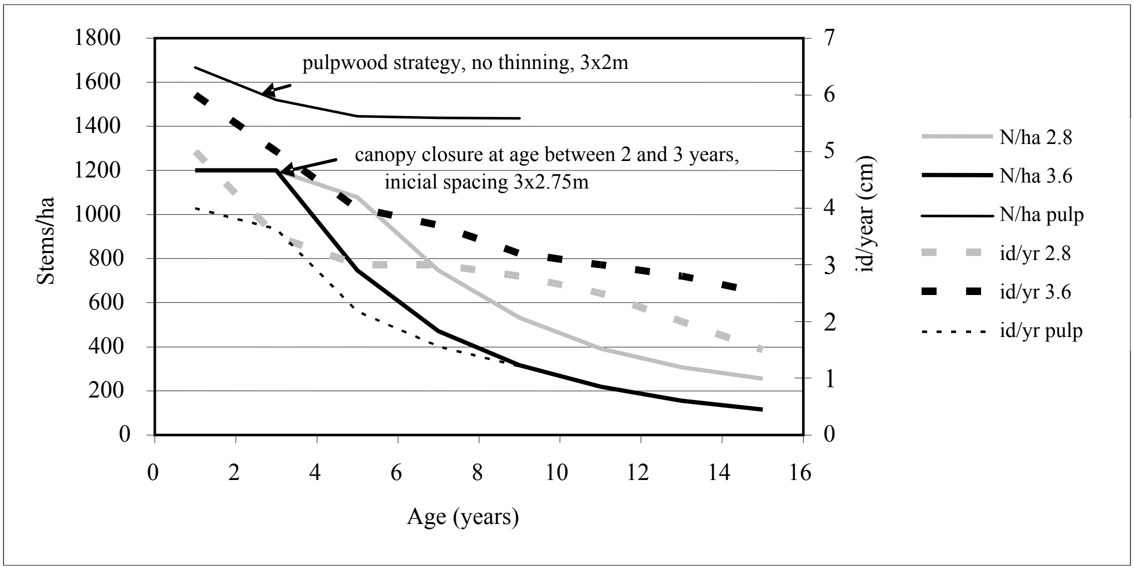

Figure 4. Reduction of stem number calculated by crown size necessary to assure a given diameter increment (id). Two sawlog management systems with thinning are compared to a classic pulpwood management system.

Figura 4. Redução do número de árvores por hectare calculado pela área da copa necessária para manter um crescimento em diâmetro pré-definido (id). Duas variantes com desbaste para a produção de toras para serraria são comparados com um manejo "clássico" para a produção de madeira para celulose.

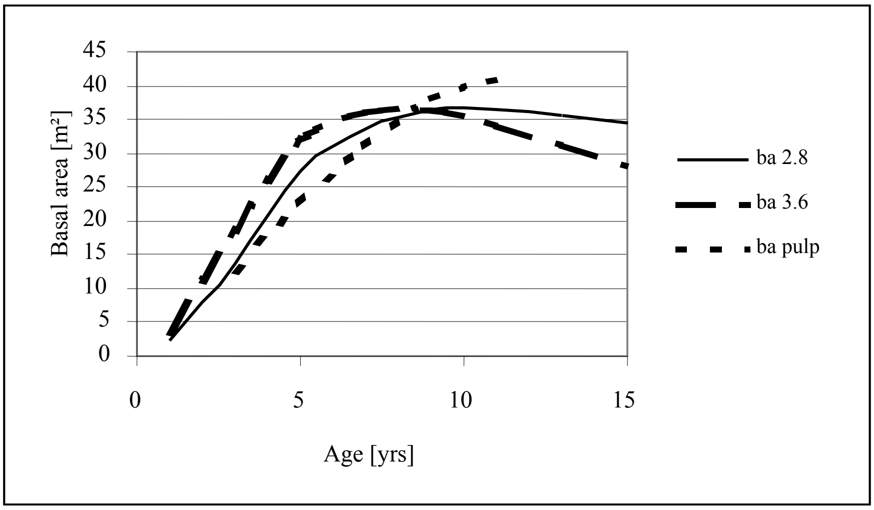

Figure 5a. Development of basal area (ba) of the 3 variants. Height growth according to yield table SI 28 of Finger (1991).

Figura 5a. Desenvolvimento da área basal (ba) das 3 varaintes. O crescimento em altura segue as tabelas de produção de Finger (1991) com um índice de sítio (IS) de 28.

Figure 5b. Development of volume (V) of the 3 variants. Height growth according to yield table SI 28 of Finger (1991).
Figura 5a. Desenvolvimento do volume (V) as 3 varaintes. O crescimento em altura segue as tabelas de produção de Finger (1991) com um índice de sítio (IS) de 28.

Decision tool to estimate age and height of pruning

In figure 6 crown recession dynamics of the two management strategies (pulpwood and thinning) are shown in function of height and diameter increment: the higher diameter increment the lower height of crown base, or the slower crown recession respectively.

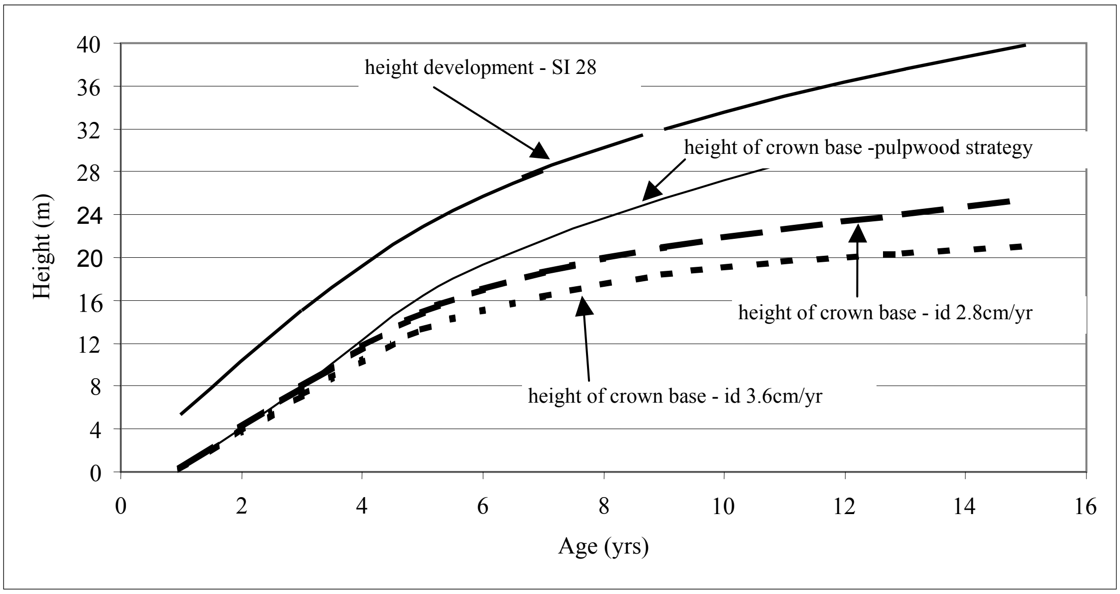

Figure 6. Development of total height and height of crown base (hcb) at a site of index 28 for the different diameter growth.
Figura 6. Desenvolvimento da altura total e a altura na base da copa (hcb) para um índice de sítio de 28 para diferentes crescimentos em diâmetro.

Figure 6 shows that no matter which thinning regimes are applied, the dynamics of crown base recession at sites of good quality and vigorous height increment begins between the first and the second year of tree age. At this stage self-pruning is only influenced by initial spacing, which in the present example is assumed to be the same. Wider spacings will retard canopy closure and cause a later beginning of this process. It can be observed that even with a 4.5 x 4.5 m planting at fertile sites the canopy closes at the age of 2.5 years because dying of branches begins due to self-shading and intra-tree competition. The crown base model offers the opportunity to calculate height and length of the living crown for different site indices and treatments. This is very important for avoiding pruning of dead branches and to calculate time of pruning, also for a second pruning at later stages.

DISCUSSION

Material and methods, modelling approach

The selected material and sampling design led to acceptable accuracy of regression estimations. Material with a wide range of characteristics (e.g. location, site, age) was used, which gives hints for a broad applicability of the model. Nevertheless, there is no guarantee that when the models are applied outside the sampling range, similar relationships could be attained.

Several studies recommend crown diameter or crown projection area and diameter growth as a fundamental empirical relationship for establishing management tools based on individual tree parameters (e.g. Duchaufour, 1903; Bonnor, 1964; Spiecker, 1991). Especially when aiming at the production of wood with high quality, stand variables have proven to be inappropriate to optimise growth and quality of trees.

Initial spacing, crown coverage and future crop trees

A parameter influencing diameter growth, crown base recession and branch diameter, which should be discussed, is initial spacing. It can be shown that at spacings of 3 x 2.75 m canopy closure occurs between age 1.5 and 3 years. This causes an early diameter increment recession and induces the dying process of branches. Plantations of *E. grandis* for the production of sawnwood or veneer with wider spacings of 3.3 x 3.0 m (1000 trees/ha) to 4.5 x 4.5 m (500 trees/ha) are already in use in Australia and Tasmania (Schönau; Cotzee, 1989). For sawlog strategies in Brazil spacings up to 5 x 5 m are discussed to consider the enormous growth vigour of young *Eucalyptus* plantations with deep soil treatments and fertilization.

As a critical point, crown coverage factor has to be mentioned. The mean value of 70 % found in this study may vary significantly for different management systems. Tree number reduction in reality may not occur like shown in table 5, because annual thinnings of a few trees do not compensate from a logistic and economical point of view. More likely one, or at the maximum two thinnings would be reasonable in practise for producing target dimensions in short rotations. This requires heavy thinnings, that means a reduction of tree number up to 50 %. Growing space available after thinning is not taken immediately by the trees. It takes a certain time after the maximum canopy closure factor is reached again, so that growth potential may be over-estimated. The dynamics of crown expansion and therefore also maximum diameter increment is correlated with site quality (Figure 2). Under unfavourable growth conditions more frequent and less intensive thinnings should be conducted in order to avoid longer periods with a low crown coverage factor, thus loosing too much volume increment. This effect could be shown in a study with *Eucalyptus grandis* at sites of medium quality (SCHNEIDER *et al.*, 1998). After heavy thinnings maintaining a basal area of only 60 % of the control plot, 300 trees per ha with a mean dbh equal or superior to 29 cm were found at the age of 189 months. The crown width model would estimate about 500 trees at this diameter.

Studies in South Africa have shown that individual trees of *Eucalyptus grandis* are able to occupy an enormous growing space in only a few years if the trees are released appropriately. It has been shown that with subsequent heavy thinnings a diameter at breast height of 80 cm can be obtained in 22 years (BREDENKAMP, 1984, *after* FLORENCE, 1996). But in this case only 30 future crop trees per ha remained, which showed a mean radial increment of 4 cm per year. The crown width model estimates a number of 25 trees per ha with such a diameter, unless such big diameters are not part of the empirical data base.

Once the target diameter is determined by the forest manager, the question is in which rotation period this goal is to be reached. In this case the model permits to calculate the growing space needed by the individual tree to achieve and maintain a certain diameter increment. With the model different management strategies can be calculated, considering also the crown expansion dynamics, which means growth limits caused by site. All calculation can be done on an individual tree basis or at stand level. Stand characteristics can be calculated assuming diameter distributions based on empirical data or on theoretical coefficients of variation.

Australian thinning recommendations for *Eucalyptus* sawlog production talk about the retention of 200 crop stems per hectare at the end of the rotation period (STACKPOLE; ALLEN, 2001), this would correspond to a target diameter of 45 to 50 cm. Slight variations in stem number can be explained by the fact that probably not all *Eucalyptus* species show the same relationship between crown width and DBH and also the canopy covering percentage is likely to vary if very strong thinnings are applied.

Studies in Europe revealed that trees with small crowns and a low radial increment show higher growth stresses (LENZ; STRASSLER, 1959), which is another fact of potential importance. This being one of the main problems of *Eucalyptus* sawnwood, lower wood tensions are to be expected with more open grown trees with big symmetric crowns (TOUZA, 2001; LISBÔA, 1993; MALAN, 2000; SCHÖNAU; COTZEE, 1989). This could even improve lumber recovery rate and increase net added value.

Pruning

It can be stated, that self-pruning of *Eucalyptus* is not good enough if the aim is production of valuable wood. This problem may be even more severe if wider initial spacing and strong thinnings are applied to reach bigger tree dimensions in short rotation periods.

Wide initial spacings lead to high growth vigour resulting in longer and therefore bigger branches. Knots in the wood cause defects in the internal wood structure and therefore lead to a loss of quality. Physical wood properties like stiffness and strength will be negatively affected by the fibre interruption or deviation because of checks or knots, reducing the utilisation of the wood for construction purposes, with the consequence of downgrade and lower prices for sawnwood. If branches of eucalypts are pruned while still green, the risk of gum pockets may be reduced and quantity of clearwood will increase significantly. As a conclusion pruning strategies have to be oriented at the height of the base of the living crown.

For optimizing time and efficiency of green pruning one has to know how the dying process under different management regimes occurs. The model predicting height of crown base may help to

- predict at what tree heights the branches begin to die if different management strategies are applied;
- avoid pruning of dead branches with its negative consequences for wood quality;
- reduce dimension of the knotty core;
- optimise time of pruning with special regards to the wood in the centre with lower quality even when branch free (juvenile wood);
- estimate how much of living crown can be removed without consequences for diameter and height increment.

The model for predicting height of crown base can be used to calculate time and height of pruning for different management regimes and different height growth dynamics. Knowing the diameter increment (determined by the crown size which is regulated by different spacings or thinning regimes) and tree height (influenced by site quality and/or genetics), development of green crown base can be calculated.

For the most valuable part of the stem a very early first pruning should be conducted at the age between one and two years. Under Brazilian growth conditions tree heights range between 8 and 15 m at this age, so that a first pruning up to 4 or 5 m does not affect tree growth to much. Several Australian and South African works show that pruning up to 50 % of the living crown does not cause a remarkable effect on height and diameter growth (BREDENKAMP *et al*., 1980; PINKARD; BEADLE, 1998a; SCHÖNAU, 2002; WIRTHENSOHN; SEDGLEY, 1998). Another reason for early pruning is that a close relationship between branch diameter and wood defects can be found (PINKARD; BEADLE, 1998a; WARDLAW; NEILSEN, 1999). High pruning is only recommended on highly productive sites (BREDENKAMP *et al.*, 1980; SCHÖNAU, 2002; STACKPOLE, 2001), otherwise the part of branch free wood that will be produced at the upper stem can not compensate the additional financial input. It must be considered that older trees show larger crowns and bigger branch diameters, increasing the risk of wood defects.

The authors mentioned above recommend pruning small and living branches in order to limit defects like decay. The pruning should be accompanied by an early thinning releasing the selected future crop trees. Knowledge of the process of branch death at varying diameter and height increments resulting from different management regimes and sites will help to manage the timing of pruning.

Economic considerations

Eucalipt solidwood production means a trade-off between maximising volume production of the stand and the conduction of big trees with high aggregated value. In general, trees with bigger dimensions compensate the loss of volume by a much higher value aggregation and higher lumber recovery rate while being processed. At a first view it may be advantageous to apply thinnings to pulpwood stands too in order to improve volume increment. It must be considered that the spacings and treatments were not only based upon a maximized volume production, but also to optimise fibre quality which may change with higher diameter growth rates. Beside this thinnings require additional investments and work input, which from an economic and logistic point of view may influence the decision of *Eucalyptus*-wood producing companies. But it could be shown by Seling *et al.* (2001) that clearwood strategies may offer interesting economic options compared to traditional pulpwood strategies, because of higher roundwood prices, lower harvest costs and higher value aggregation of the final products.

This contradicts the conclusions made by Gerrand *et al*. (1993) for the Australian eucalypt sawlog production, but the situation in Brazil is quite different. According to the authors, the most sensitive factors for a positive financial return are site productivity and distance to market. The volume increment in most cases is superior to the minimum limit of 15 m^3/ha/yr in Brazilian *Eucalyptus* plantations, making short rotation periods possible. Beside this, the vertical structure of enterprises, which means that forest owner, manager and wood processing industry are in the hand of one enterprise, assures a high optimisation potential of the whole production and logistic chain. Under these circumstances a clearwood sawlog regime based on early age standing may produce a positive return higher than for pulpwood production, even if combined with a cost intensive pruning.

CONCLUSIONS

The strong correlation between crown width and diameter at a height of 1.30 m found for *Eucalyptus grandis* can be used to perform decision supporting tools for estimating number of future crop trees with a determined target diameter. The performance of the model allows calculation of different scenarios of management strategies of special interest for *Eucalyptus* sawlog production. Maximum crown expansion is determined and therefore diameter growth is limited by site productivity. Eucalypt sawlog production in short rotations under Brazilian growth and market conditions offers an alternative option to pulpwood. The crown width model allows the calculation of selective thinnings based on individual trees. This may help to improve wood quality and reduce labour input and costs. Moreover, it offers an interesting methodological approach for single tree management in native *Eucalyptus* dominated forests. Spacing indices and yield tables generally used to maximize volume of wood production may not be appropriate for a sophisticated management with the aim of high quality timber production.

Eucalyptus grandis does not show a self-pruning good enough for high quality timber production, even growing under high competition as it was investigated in stands managed for pulpwood. The presented model for predicting dynamics of crown base recession is influenced by height growth, i.e. site quality, and diameter increment. While diameter increment shows a retarding effect on dying of branches, culmination of height increment in the first 3 years cause strong inter and intra-tree competition, forcing self-pruning dynamics. For high quality sawlog production in Brazil a wide initial spacing (500 to 800 plants/ha) at sites of good to very good quality should be chosen. On sites of lower productivity more trees should be planted to avoid long periods with low crown coverage, since crown expansion shows not the same dynamics at such sites. Wider initial spacings assure that the high diameter increment potential of *Eucalyptus grandis* for the first 3 years is maintained. Intensity and time of thinnings may be calculated with help of the crown width model and conducted according to the production objectives target diameter, number of future crop trees and rotation period, considering limitations induced by site quality. These limits can be taken from height curves or yield tables available and adapted for different stands or provenances. According to these objectives height of living crown base can be calculated and pruning strategies may be adapted to specific diameter and height growth resulting from different management strategies and sites. Since it could be shown that green pruning is absolutely necessary for high value timber production, wider initial spacings avoid a too early dying of branches. It could also be shown that distances of 4.5 m in and between the planting rows do not lead to critical branch diameters above 3 cm. The model is also able to provide an estimation of the height of pruning, so that pruning intensity can be optimised. The 50 % limit of green crown length should be maintained to avoid loss of diameter and height increment. Otherwise pruned trees will get under strong competition by neighbouring trees without loss of assimilating biomass. This way high quantities of knot free wood can be produced in short rotations of 15 years. Open questions are still which wood quality results from very fast growing *Eucalyptus* trees in terms of dimension of the core juvenile wood, coloration, sapwood and hardwood as well as elastic and static wood properties. Further research is needed on these topics.

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