SILVA FENNICA

Silva Fennica 43(4) research articles

www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

Growth Strain in *Eucalyptus nitens* at Different Stages of Development

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Biechele, T., Nutto, L. & Becker, G. 2009. Growth strain in *Eucalyptus nitens* at different stages of development. Silva Fennica 43(4): 669–679.

Eucalypts are renowned for their high growth stress levels. These stresses cause splitting, warping and dimensional instability when cutting, processing and drying the wood. In Chile, large *Eucalyptus nitens* plantations can be found, which, due to these problems, are scarcely utilised for solid wood products (veneer, sawn wood). This study aims to determine the factors influencing growth stress at different stages of tree's development, and to identify whether the factors influencing growth stress change over time. In five stands of different ages, growth strain, as an indicator of growth stress, was measured at different tree heights with the single hole drilling method. The tree variables DBH, tree height, slenderness (height/diameter ratio) and crown parameters also were measured. A correlation analysis of tree variables and growth strains was undertaken. The results obtained indicate a high variability in growth strain values. It was concluded that growth strain is not correlated with a single growth parameter, but with a combination of factors that variously influence it at different ages and tree heights.

Keywords growth stress, growth strain, *Eucalyptus nitens*, stages of development, sawnwood
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Reveived 21 January 2009 **Revised** 23 June 2009 **Accepted** 6 July 2009
Available at http://www.metla.fi/silvafennica/full/sf43/sf434669.pdf

1 Introduction

Large *Eucalyptus globulus and E. nitens* plantations exist in Chile. The pulp and paper industry mainly is focused on the utilisation of *Eucalyptus globulus* for the production of high quality pulp, and requires only a small percentage of *E. nitens*. As a consequence of the pulp and paper industry's limited interest in *E. nitens,* large areas of older *E. nitens* stands are still present in the southern part of Chile, some of which already have attained sawlog dimensions. An alternative use needs to be found for this resource. Aside from reconstituted wood products, the generation of higher value products such as veneer or sawn timber may be an option for the future.

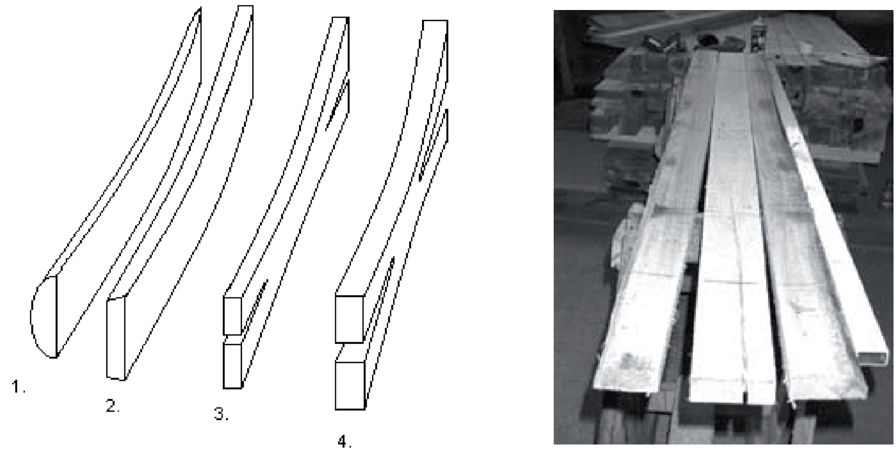

Fig. 1. Bow and spring (1. and 2.), and end split (3. and 4.) occur frequently during processing of sawlogs with high tensions.

Problems arise when processing wood and drying timber with high growth stresses. Defects such as log end splitting, distortions, cracks (Fig. 1), checking and collapse are often reported (Yao 1979, Archer 1986, Yang and Waugh 1996, Touza 2001). Thus, an analysis of the potential to reduce growth stress is of major interest if one aims to increase the utilisation of *E. nitens* wood. Several scientific investigations of growth stresses in eucalypts have been conducted. Most have focussed on trees of harvestable size (Vignote et al. 1996, Wellhöfer 2001, Lemos 2002, Touza Vázquez 2004). Although the development of growth stress is a dynamic process, few studies have investigated tree growth stress at different stages of development. The literature suggests that growth parameters such as crown width, crown area, crown eccentricity, crown length, tree height and DBH may influence growth stress. These parameters also describe individual tree competition in stands. Authors' reports about which parameters affect growth stresses to a larger degree are conflicting.

The origin of growth stress has been analysed extensively. Firstly, the maturation of the wood cells causes stress, termed "maturation stress", and, secondly, crown weight and bending as a result of wind cause "supported stress". During the maturation of the newly formed wood, the cells, which grow every year on the stem periphery, contract longitudinally while the lignified wood cells already formed impede this contraction. This causes tension which contributes to the protection of new wood cells from bruising. Inside the tree, the stress attains equilibrium. In keeping with the theory from Kübler (1959a), growth stresses are highest at the stem periphery to prevent non-lignified cambium cells becoming compacted in the event that external forces, such as wind, cause young trees to bend. This theoretical approach says that a tree is in perfect balance when a tension zone, at a maximum close to the bark, and a compression zone in the centre of the tree occur, resulting in a line of zero tension between the two zones at two thirds of the radius (2/3 r) (Figs. 2 and 3).

Kübler's theory explains well the different defects of warping and distortions when logs under high tension are processed.

Based on this theory, peripheral growth stress is estimated from growth strain release, which, unlike growth stress, can be measured directly with the CIRAD-Forêt growth strain gauge method (Yang and Waugh 2001). Thus the growth strain values may be used as growth stress indicators (GSI). Kübler (1959a) maintains that processing and drying timber from trees with low surficial strains present minimal problems, yet practice proves this untrue in many cases as trees with rather low surficial growth strains do occasionally

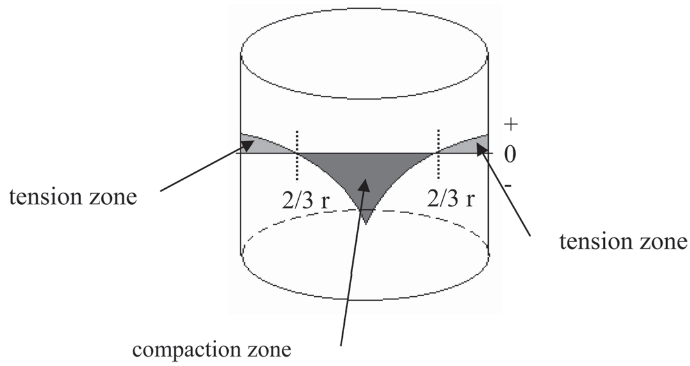

Fig. 2. Distribution of growth stress in the stem with tension (+ value) and compression (– value) forces in perfect balance according to Kübler's theory (Kübler 1959b).

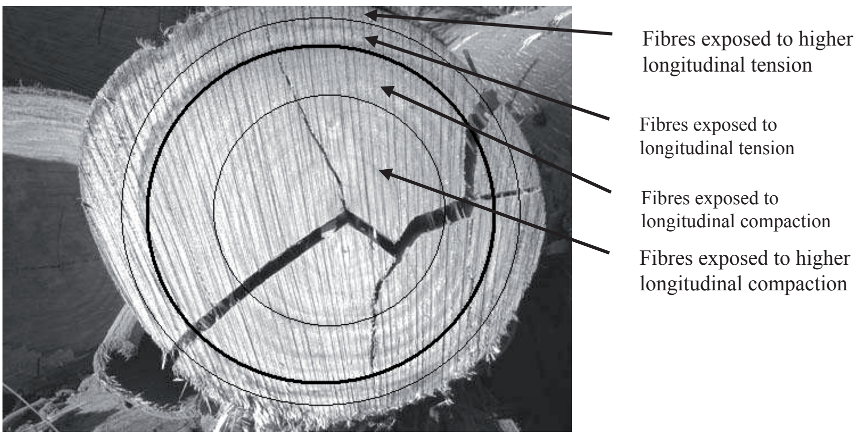

Fig. 3. Radial distribution of tension and compaction zones in the stem cross-section.

warp and split. Okuyama (1997) shows that the tension and compression zones in trees rarely are balanced perfectly in their distribution as assumed by Kübler (1959a). According to Kübler 1959b, tension wood at the stem periphery is reversible because, with ongoing diameter growth, the "tension zone" becomes a "compression zone" as it graduates to the inner two-thirds of the stem radius. Yet, in some cases, growth stresses are such that tension wood is formed. In hardwoods, the tension wood comprises cells of a different type. In some species, a G-layer is formed, which is lignin-free, gelatinous and capable of swelling (Sachsse 1964, Beimgraben 2002). In many mature eucalypts, a special crystalline type of cellulose with a different microfibril angle is formed (Baillères 1994). In this case, the substantial amount of tension wood formed results in an irreversible conversion of the cells embedded in the wood tissue. In such cases, Kübler's assumptions are invalid. Therefore, conclusions about real growth stress distribution in the trees drawn from measurements of the peripheral growth strain only may be incorrect.

The semi-destructive nature of gauge measurements prohibits repeated measurement at the one tree height, thereby ruling out the possibility of developing time series of tree growth stress. Thus, this method only permits the measurement of tree parameters from which inferences about growth stress development at different life stages of a tree can be made.

To assist decisions towards the development of solid wood management programs for the production of sawlogs with minimal growth stress at each stage of development, this study aims to investigate whether a dynamic change in the relationship between growth parameters and growth stress levels over the lifespan of eucalypt trees occurs. To achieve this, the tree parameters that may influence growth stress in eucalypts are analysed. Since growth stress may vary at different stem heights, tree parameters are measured along the length of the tree.

2 Material and Methods

The study is based on the analysis of peripheral growth strain measurements from 50 *Eucalyptus nitens* trees from the Pre-Andean zone of the 8th Chilean region. In total, five stands at the ages 3, 7, 9, 10 and 14 years were selected. Homogeneity of the sites and growth conditions was important in the selection of the stands to ensure comparability of data for the different stages of development. Each sample in a stand consisted of 10 trees with different social positions (5 co-dominant, and 5 dominant or pre-dominant). Growth strain was measured at 1.3m, at 25% and 50% of total tree height in the north, south, east and west directions.

Measurements of individual tree growth parameters such as crown width, crown area, crown eccentricity, crown length, tree height and DBH, and also slenderness (height/diameter ratio) were taken. The range in DBH and tree heights spanned 8 to 44 cm and 9 to 45 m respectively. Crown size and crown eccentricity were derived from crown projection area measurements. From tree and crown distribution data, maps were generated with the software program Arc View© to analyse individual crown competition and its effect on peripheral growth strain. The crown eccentricity variables CCG_D (direction from crown centre) and CCG_E (distance from crown centre) were also calculated dividing the crown surface in eight triangles and calculating the balance point of each one. The average distance of the balance points of the triangles was taken to determine the crown eccentricity of the tree.

Following the procedure developed by Fournier (1994), growth strain measurements were taken with the CIRAD-Forêt growth strain gauge, which detects longitudinal growth strain at the stem periphery by taking measurements on the stem under the bark. By cutting the fibres between two nails with a drill, stress is released, and the disbanding between the nails is measured in micro

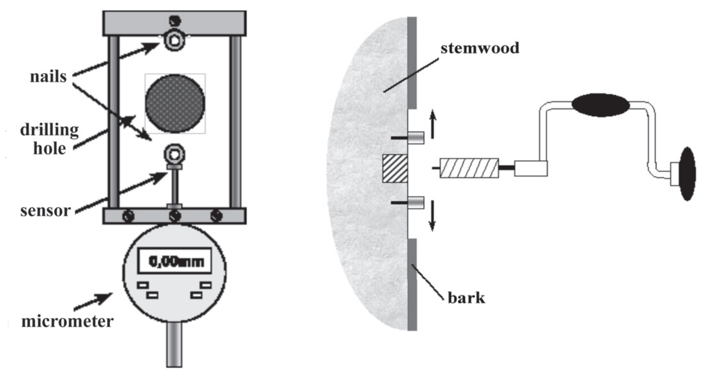

Fig. 4. Growth stress measurement with CIRAD-Forêt growth strain gauge. Front view (left) and side view (right).

metres (Fig. 4). The values measured indicate the longitudinal growth strain on the stem periphery. According to Kübler (1959a), growth strain can be adopted as an indicator of growth stress levels (GSI). Peripheral growth strain indicates the actual stress level at the outer part of the tree where, according to Kübler (1959a), stress is highest. Most studies and literature available about growth stresses used this method. To make this study comparable to others this approved method has been used. Longitudinal growth stress can evoke cracking and end splitting of logs (Cassens 2004).

The growth strain data obtained for the correlation analysis were stratified by age class, and evaluated statistically with the software package SAS 9.2©. Statistical analysis was undertaken to obtain relationships between tree growth parameters and growth strain values.

In a first step, mean and maximum values of growth strains in each age class and at the different tree heights were calculated. Therefore the mean growth strain value of the four cardinal points in each stem height per tree was taken.

In a next step a correlation analysis was carried out to detect the relationships between growth parameters and growth strains. Therefore the mean values of each stem height of the tree were correlated with the growth parameters of this tree. The maximum growth strain value on the other side reflects the highest measured growth strain value within the four cardinal points in each height.

Tables 2 to 4 show Pearson correlation coefficients between growth strain and tree parameters at different stem heights. Mean and maximum values were chosen because they described growth strains best. Maximum growth strain levels indicate the occurrence of tension wood (Yang and Waugh 2001).

3 Results

The growth strain values vary over time and at different stem heights (Table 1). While mean growth strain at 1.3m height was moderate in the youngest trees, it increased with age to 10 years when the trees reach heights of about 35m. At age 14, when trees achieved sawlog dimensions, the GSI is significantly lower. Such a trend was

Table 1. Growth strains (GSI = growth stress indicators; change in microns) measured for 5 age classes, and at 3 stem heights: mean GSI value (average of 4 measurements), below the average maximum GSI values at each tree height and the coefficient of variation (CV) in %.

Age (years)	Average tree height (m)	Average DBH (mm)	Height 1.3 m GSI (microns)	Height 25 % GSI (microns)	Height 50 % GSI (microns)
3	12.9	111	Mean: 112 Max.: 192 CV %: 48.9		
7	23.7	173	Mean: 160 Max.: 358 CV %: 31.1	Mean: 100 Max.: 150 CV %: 38.7	Mean: 104 Max.: 145 CV %: 65.4
9	32.3	261	Mean: 284 Max.: 456 CV %: 53.1	Mean: 147 Max.: 227 CV %: 38.0	Mean: 151 Max.: 440 CV %: 72.4
10	35.1	294	Mean: 395 Max.: 820 CV %: 36.9	Mean: 129 Max.: 180 CV %: 27.1	Mean: 122 Max.: 160 CV %: 36.2
14	42.0	381	Mean: 160 Max.: 248 CV %: 33.2		

not found for the GSI at the upper height of trees aged 7 to 10 years. Then, stress levels remained more or less constant. Up to age 10 years, the GSI values were always highest at 1.3m height. The mean values of the maximum growth strain for each height and age class indicated that, between 7 and 10 years of age, trees were prone to tension wood formation. Growth strain measurement is used as an indicator for growth stresses (Yang and Waugh 2001) and hence may be used to estimate if the probability of tension wood formation is high or not.

3.1 Growth Strain at 1.3m Tree Height

At first, no common factors influencing growth strain across all age classes were found (Table 2). At the age of 3 years slenderness was the only variable that correlated significantly with growth strain. At age 7, and 9 years, crown eccentricity factors influenced growth stress, whereas at age 10 years, a positive correlation of tree height and tree dominance with GSI was found. At age 14 years, DBH, tree height, crown base height and tree dominance in the stand were found to correlate with GSI. In general, the older stands (or individual trees) develop more complex relationships between tree parameters and growth strain. This means that, for older trees, especially for trees with sawlog dimensions, a multivariate approach may prove useful for explaining growth strains.

3.2 Growth Strain at 25% of Tree Height

Unfortunately no growth strain measurements above 1.3m stem height could be taken in the 3- and 14-year-old stands. In the 14-year-old stand, in particular, where some of the trees had already reached sawlog sizes, growth strain analysis would be expected to contribute to a better understanding of growth strain distributions along the stem.

Clearly, the correlations of the tree variables with growth strain change at 25% of total tree height (Table 3). At age 7 years, crown eccentricity variables also are correlated with GSI. At age 9 years, tree height, also an indicator of tree dominance, correlated positively with GSI, whereas, at age 10 years, almost all tree parameters listed correlated with measured growth strains. Thus, again, the tendency for increased complexity in the interactions between growth parameters and GSI in older trees again is found.

3.3 Growth Strain at 50% of Tree Height

In Table 4, crown eccentricity at 50% of tree height is still the major factor at age 7, while at

Table 2. Growth strain measured at 1.3m height. Pearson correlation coefficients: Prob > |r| under H0: Rho = 0. Level of significance: * < 0.1, ** < 0.05, *** < 0.01.

Age (years) Tree height (m)		DBH	Height	H/D	CPA	CD	CB	H_dom_p	CCG_D	CCG_E
3 years	GSI13 mean	-	-	0.58*	-	-	-	-	-	-
12.9 m	GSI13 max	-	-	0.58*	-	-	-	-	-	-
7 years	GSI13 mean	-	-	-	-	-	-	-	0.60*	-
23.7 m	GSI13 max	-	-	-	-	-	-	-	-	-
9 years	GSI13 mean	-	-	-	-	-	-	-	-	–0.63**
32.3 m	GSI13 max	-	-	-	-	-	-	-	-	–0.74***
10 years	GSI13 mean	-	0.65**	-	-	-	-	0.65**	-	-
35.1 m	GSI13 max	-	0.64**	-	-	-	-	0.64**	-	-
14 years	GSI13 mean	-	0.67**	-	-	-	0.58**	0.67**	-	-
42.0 m	GSI13 max	0.59*	0.62*	-	-	-	0.63*	0.62*	-	-

DBH = diameter at 1.3m, H/D = height/diameter ratio, CPA = crown projection area, CD = crown diameter, CB = crown base height, H_dom_p = dominant height of 100 thickest trees/ha, CCG_D = direction of crown center of gravity, CCG_E = distance from center of crown gravity, GSI 13 mean/max = mean/max growth strain at 1.3m height

Table 3. Growth strain measured at 25% of tree height. Pearson correlation coefficients, Prob > |r| under H0: Rho = 0. GSI 25 mean/max = mean/max growth strain at 25% of tree height.

Age (years) Tree height (m)		DBH	Height	H/D	CPA	CD	CB	H_dom_p	CCG_D	CCG_E
7 years	GSI25 mean	-	-	-	-	-	-	-	0.58*	0.68**
23.7 m	GSI25 max	-	-	-	-	-	-	-	0.65**	0.62*
9 years	GSI25 mean	-	0.54*	-	-	-	-	0.55**	-	-
32.3 m	GSI25 max	-	0.61*	-	-	-	-	0.61**	-	-
10 years	GSI25 mean	0.62*	0.67**	–0.57*	0.63*	0.67**	-	0.67**	-	-
35.1 m	GSI25 max	0.60*	0.67**	-	0.65**	0.67**	-	0.67**	-	-

Table 4. Growth strain at 50% of tree height. Pearson correlation coefficients, Prob > |r| under H0: Rho = 0. GSI 50 mean/max = mean/max growth strain at 50% of tree height.

Age (years) Tree height (m)		DBH	Height	H/D	CPA	CD	CB	H_dom_p	CCG_D	CCG_E
7 years	GSI 50 mean	-	-	-	-	-	-	-	-	0.67*
23.7 m	GSI 50 max	-	-	-	-	-	-	-	-	0.77**
9 years	GSI 50 mean	-	-	-	-	-	-	-	-	-
32.3 m	GSI 50 max	-	-	-	-	-	-	-	-	-
10 years	GSI 50 mean	0.56*	-	–0.62*	0.64**	0.66**	-	-	-	-
35.1 m	GSI 50 max	-	-	–0.57*	0.60*	0.63**	-	-	-	-

9 years of age no significant correlation between growth parameters and GSI could be found. The 10-year-age stand again showed complex interactions between GSI and growth parameters, particularly for correlations with DBH, slenderness and crown size parameters.

4 Discussion

To discuss the influence of growth strains on wood properties, it is useful to have a closer look at the growth strain levels found in other investigations on hardwood species. There are no studies available at what growth strain level the liberation of growth stresses while processing the logs cause defects result in degrading of lumber quality. Of course the other forces also may influence lumber quality, like drying stresses for instance. In combination with high growth stresses they may lead to warping and splitting of lumber (Ormarsson and Dahlblom 2008). Some logs are less prone to splitting and warping than others, even though growth strain levels are comparable or higher (Brazilian tree breeders, pers. comm.).

In Table 5, GSI values taken from different studies of eucalypts and other tree species are listed. Between the maximum values, the genus *Eucalyptus* reveals the highest growth strain levels compared to other species. Even so, there is a broad variation between eucalypts, high growth strains can develop in *Eucalyptus nitens*, which may have a severe impact on solid wood utilisation. Some variation is due to the measurement of trees at different ages and stages of development.

The correlations between growth parameters and peripheral growth strain values (GSI) are rather low. It can be assumed that more than one tree parameter affects growth strains, especially in older stands. A multivariate approach, which also reflects the interactions among tree parameters, might be useful in modelling. Nutto and Touza

Table 5. Minimum and maximum GSI from different studies measured with the growth strain gauge.

Tree species	Author	GSI min. (microns)	GSI max. (microns)
Eucalyptus nitens	Present study (2007)	20	820
E. nitens	Valdes (2004)	19	290
E. globulus	Nutto and Touza Vázquez (2005)	40	230
E. globulus	Touza Vázquez (2004)	60	140
E. globulus	Raymond et al. (2002)	10	400
E. globulus	Vignote et al. (1996)	20	300
E. grandis, *E. saligna*, *E. citriodora*	Wellhöfer (2001)	50	80
E. grandis, *E. urophylla*	Lemos (2002)	20	650
E. grandis	Lima et al. (2004)	50	80
Fagus sylvatica	Beimgraben (2002)	10	210
F. sylvatica	Bleile (2006)	30	260
Populus spp.	Devlieger and Quintana (2006)	100	140

Vázquez (2005) came to the same conclusion in their investigations on growth strain of *E. globulus* at different ages. Their results indicate the importance of the stage of development when determining the influence of tree parameters on growth strain.

The objective of the study was to identify tree growth parameters influencing growth strain to avoid the formation of tension wood during a rotation. This would be achieved by adopting silvicultural approaches that help minimise growth stresses. In sawlog management regimes, rapid diameter growth is crucial for shortening rotation length. Therefore the dominant trees with more vigorous diameter growth are of special interest.

The results show that, in very young stands (age 3 years), slenderness is the most important factor for keeping growth strains low. At this stage the growth strain levels still tend to be low. However, critical growth stress values, responsible for the formation of reaction wood, can be reached already. A critical growth stress level would be if the liberation of growth stresses while processing and drying the wood lead to irreversible defects.

To reduce the ratio of tree height to tree diameter, a wider spacing can be chosen to reduce the competition among trees, creating more growing space and thereby enhancing diameter increment. This reduces slenderness and increases the stability of the future crop trees. At this stage of development, juvenile wood with poor strength properties still is formed (Malan 1991a), which means that wood quality has not been impaired as yet. In the stands at age 7 years, the influential growth parameters have changed already. Crown symmetry has become the most important factor for keeping growth strains low. This is true for growth strains measured at all stem heights. At height 1.3m, the maximum GSI values are already very high, at which point symmetric crown development becomes a priority. At this stage of development, tree spacing and thinning should enable trees to form symmetrical crowns to achieve homogeneous competition conditions and by this reduce GSI. Kübler (1987) and Wellhöfer (2001) see in crown reorientation one of the main reasons for growth stress generation. Therefore Nutto and Maestri (2002) recommend in their study with *E. globulus* to maintain a constant competition to ensure a uniform crown development. At the age of 9 and 10 years, the relationship between growth parameters and growth strain becomes more complex. For the 9-year-old stand, growth strain at 1.3m still is most influenced by crown symmetry. For the upper heights in these stands, as well as for the 10-year-old trees, tree height and social position of the tree become more important. The results show clearly that higher trees in dominant positions in the stand are prone to have higher growth strain. This is because dominant trees more likely are affected by their higher exposure to wind, which causes crown surface roughness. However, this stage is crucial for the wood quality as undesirable tension wood may be formed. The results of this study indicate that trees with a higher slenderness show lower growth strains. At 1.3m height, the GSI values can reach critical levels. As a consequence, moderate thinnings should be implemented to produce more homogeneous conditions, and ensure the presence of more co-dominant to dominant trees in stands. Examples of sawlog management regimes, in which the trees have been freed of competition entirely, do not exist. The analysis of such trees would reveal whether the effects of growth strain variation are the same. An investigation of clonal stands would be of interest to determine whether in more homogeneous stands by virtue of the identical genetic origin, variation of growth strain is lower.

For the 14-year-old stand, the parameters, that influence growth strain are similar to those for 10-year-old trees, at least at tree heights of 1.3m, but the growth strain levels are significantly lower than for younger stands. The focus should be placed on less dominant trees because of their lower growth stress levels. This contradicts many studies presented in the literature, in which a tendency towards lower growth strains with decreasing competition is described, i.e., for the dominant trees (Saurat and Gueneau 1976, Ferrand 1982, Cardoso Junior et al. 2005). Most of the studies were carried out in stands comprising trees with harvestable dimensions (Vignote et al. 1996, Wellhöfer 2001, Lemos 2002, Touza Vázquez 2004, Valdes 2004). Since the study could show that growth strains are highly dynamic, one cannot claim that 14-year-old trees, even the dominant ones, are comparable to more open grown eucalypts in sawlog management stands with less competition. The slenderness of the 45m high trees is still greater than 100, which also indicates that the future crop trees at this age are unstable because of their low DBH values (Nutto and Touza Vázquez 2005). It is often stated in the literature that age is important because growth strains decrease as trees age. Most of these studies focus on growth strain measurements at 1.3m height. This is also true for the trees analysed in this study. Nutto and Touza Vázquez (2005) showed, at least for *E. globulus*, that growth strain levels in fact decrease at 1.3m height, but that growth stress level may increase dramatically at upper stem heights. This was confirmed by other studies of different eucalypt species and beech (*Fagus sylvatica*) (Beimgraben 2002, Lemos 2002, Raymond et al. 2002, Bleile 2006). Data about growth strains at upper stem heights for the 14-year-old trees are unavailable.

The study represents the first attempt to obtain more detailed information about the dynamic of growth strains at the stem periphery at different stages of tree development. As only a limited number of trees were available, the results will need to be confirmed by further research.

5 Conclusions

The correlation analysis shows a wide variation of factors influencing growth strain in *E. nitens* trees at different stages of development. At different development stages, the parameters influencing growth strain in the stem change in the longitudinal and radial direction. Further growth stress investigations of *E. nitens* in stands of different ages are required to support or contradict the conclusions of this study, which have been made after sampling 50 trees, and are therefore only preliminary. Nevertheless the results show that more than one parameter influences growth stress. In the literature, most investigations of factors influencing growth stress are restricted to one stage of development. In this study, we found that the parameters affecting growth strain differ markedly at different stages of development. Therefore, multiple parameters should be considered for the important stages of development to avoid the production of irreversible tension wood cells inside the stem of younger trees, which ultimately can cause warping and splitting of sawlogs. Therefore silvicultural prescriptions that maintain a reduced growth stress levels by managing the relevant tree parameters can lead to lower internal stem growth stress levels, and facilitate a higher utilization of eucalypt round wood.

Acknowledgements

The authors would like to thank Eduardo Navarrete (Universidad de Concepción Departamento Forestal Los Angeles, Chile) for the access to field trials and Helen Desmond for correcting the English manuscript.

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