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## Patterns of distribution of longitudinal and tangential maturation stresses in *Eucalyptus nitens* plantation trees

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8  
9 **Patterns of longitudinal and tangential maturation stresses in *Eucalyptus nitens***  
10 **plantation trees**

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27 **Abstract**

- 28 • **Context:** Tree orientation is controlled by asymmetric mechanical stresses set during wood  
29 maturation. The magnitude of maturation stress differs between longitudinal and tangential  
30 directions, and between normal and tension woods.
- 31 • **Aims:** We aimed at evaluating patterns of maturation stress on eucalypt plantation trees and their  
32 relation with growth, with a focus on tangential stress evaluation.
- 33 • **Methods:** Released maturation strains along longitudinal and tangential directions were  
34 measured around the circumference of 29 *Eucalyptus nitens* trees, including both straight and  
35 leaning trees.
- 36 • **Results:** Most trees produced asymmetric patterns of longitudinal maturation strain but more  
37 than half of the maturation strain variability occurred between trees. Many trees produced high  
38 longitudinal tensile stress all around their circumference. High longitudinal tensile stress was not  
39 systematically associated with the presence of gelatinous layer. The average magnitude of  
40 released longitudinal maturation strain was found negatively correlated to the growth rate. A  
41 methodology is proposed to ensure reliable evaluation of released maturation strain in both  
42 longitudinal and tangential directions. Tangential strain evaluated with this method was lower  
43 than previously reported.
- 44 • **Conclusion:** The stress was always tensile along longitudinal direction and compressive along  
45 tangential direction, and their respective magnitude was positively correlated. This correlation  
46 does not result from a Poisson effect but may be related to the mechanism of maturation stress  
47 generation.

## 1 **Introduction**

### 2 *Origin and biological function of maturation stress in wood*

3 After the cells division in the cambium and their differentiation, the maturation of the newly formed  
4 wood cells induces their tendency to shrink longitudinally and swell transversally (Fig. 1a) (Archer  
5 1987). These strains being mostly impeded by their adherence to the older rigid cells, the cell  
6 maturation process results in a mechanical state of longitudinal tensile stress and tangential  
7 compressive stress in mature wood at tree periphery (Fig. 1b). From a mechanical viewpoint, these  
8 maturation stresses are “pre-stresses”, *i.e.* stresses that occur during the formation of the material,  
9 prior to any external loading. Pre-stresses are beneficial for the living tree since they optimize the  
10 behaviour of wood in response to external loading. As a honeycomb cellular material, wood has a  
11 high tensile strength along the fibre direction but is comparatively weak in compression. Thus, if  
12 wood is subjected to local axial compression, as occurs in the inner side of a bent stem, axial buckling  
13 can be avoided by tensile pre-stresses (Bonser and Ennos 1998). Similarly, in the tangential direction,  
14 wood can withstand compression without major damage by bending its cell walls, whereas in tension,  
15 rupture and crack propagation can easily occur. Tangential compressive pre-stress helps preventing  
16 this situation.

17 These maturation stresses are also useful to trees for their postural control (Moullia et al. 2006). Trees  
18 are able to control the level of maturation stress in the produced wood, and to generate asymmetrical  
19 axial stress around the stem circumference. This asymmetry generates a bending moment allowing  
20 movement of the stem towards verticality or any preferred direction, or just to maintain a defined  
21 angle by compensating for the effect of the increasing self-weight (Almérás and Fournier 2009). To  
22 achieve a high asymmetry, angiosperms produce very high level of tensile longitudinal stress in the  
23 inner side of the axis to be bent, through the production of a dedicated wood called tension wood. In  
24 tension wood, stresses can be more than 5 times higher than in normal wood. Tension wood is  
25 characterised by chemical and ultra-structural changes such as a lower lignin content, more crystalline  
26 cellulose and a lower microfibril angle than in normal wood (Onaka 1949). In some species a specific  
27 unligified cell wall layer is formed, named gelatinous layer (G-layer). This layer is characteristic of  
28 tension wood in most temperate species. However, many species, especially in the tropical area where  
29 most diversity can be found, have tension wood without G-layer (Clair et al. 2006b; Onaka 1949;  
30 Yoshida et al. 2002). Although this criterion is generally common to an entire genus, *Eucalyptus* has  
31 some species where tension wood with G-layer has been detected (e.g. *E. nitens*) and many species  
32 producing tension wood having a lignified layer instead of the characteristic G-layer (Baillères et al.  
33 1995; Scurfield 1972).

1

2 *Technological consequences of maturation stress*

3 The production of maturation stress in the newly formed wood layers is always balanced by a change  
4 in the state of stress in inner layers (Fig. 1b). Tensile longitudinal stress at the periphery induces  
5 longitudinal compression in the core of the trunk. In turn, compressive tangential stress at the  
6 periphery induces tensile tangential stress in the core of the trunk, and tensile radial stress in the  
7 whole trunk. The accumulation of these stresses during the whole tree life results in a complex stress  
8 field in the trunk, called “growth stresses” (Archer 1986; Boyd 1950a; Kubler 1987), leading to  
9 technological problems such as log-end splits and heart checks during tree felling, brittle heart, and  
10 deformations of planks during sawing (Boyd 1950b; Biechele et al. 2009; Yang and Waugh 2001;  
11 Nicholson 1973). Figure 2 illustrates log-end cracks observed few minutes after felling the tree in the  
12 eucalypts studied in the present article. These cracks are due to the combined effect of radial gradient  
13 in longitudinal growth stress and radial tensile growth stresses (Kubler 1987; Jullien et al. 2003) and  
14 clearly reduce the commercial value of logs. This problem is particularly important in eucalypt trees,  
15 that generally have very high levels of maturation stress (Baillères et al. 1995; Biechele et al. 2009;  
16 Giordano et al. 1969; Jacobs 1938; Ferrand 1982c; Nicholson 1973). As the magnitude of the growth  
17 stress field primarily depends on the magnitude of maturation stress, it is important to be able to  
18 characterize this maturation stress on standing trees in order to predict or avoid the occurrence of such  
19 problems.

20

21 *Evaluation of longitudinal maturation stress: existing methods*

22 Maturation stress at the periphery of a standing tree can be evaluated by measuring the strain  
23 generated by the release of the stress. As described in earlier reviews (Archer 1986; Kubler 1987;  
24 Yang and Waugh 2001) three main methods have been used for that. The oldest methods consisted in  
25 taking a piece of wood out of the trunk or log and measuring its change in dimension (Boyd 1950a;  
26 Ferrand 1982a, 1982c; Giordano et al. 1969; Jacobs 1938, 1945; Nicholson 1971; Nicholson 1973),  
27 More recent methods are both less invasive and more precise, and consist in applying the stress  
28 release and strain measurement locally on the standing tree. The stress can be released by creating a  
29 free surface, either by drilling a hole or by locally sawing the wood (Fig. 1b). In the so-called “single-  
30 hole method”, developed by CIRAD (Gerard et al. 1995), the displacement of two nails below and  
31 above the hole is measured, and this displacement is called growth stress indicator (GSI). This  
32 measurement (Alméras et al. 2005; Clair et al. 2003; Fournier et al. 1994; Gerard et al. 1995;  
33 Baillères et al. 1995; Biechele et al. 2009; Jullien et al. online 2012), expressed in micrometres, is not

1 directly indicating a strain but is proportional to it, with a conversion factor between 9 and 13  
 2  $\mu\text{strain}/\mu\text{m}$  (Fournier et al. 1994). Finally, the most popular method in recent studies consist in sawing  
 3 the wood above and below an area where the strain is measured, either with a displacement transducer  
 4 (Clair et al. 2006b; Fournier et al. 1994) or with a strain gage (Alméras et al. 2005; Fang et al. 2008;  
 5 Okuyama et al. 1981; Sasaki et al. 1978; Yoshida et al. 2002; Yamamoto et al. 2005). Metrological  
 6 analyses of this methods can be found in Yoshida and Okuyama (2002) and Jullien et al. (2008).

7  
 8 *Evaluation of tangential maturation stress: existing methods and theoretical considerations*

9 Most maturation stress studies concentrated on the measurement of released longitudinal maturation  
 10 strains (RLMS) to evaluate maturation stress in the fibre direction, because maturation stress has the  
 11 highest magnitude in this direction and is directly involved in major biological functions of wood  
 12 such as gravitropism (Coutand et al. 2007; Yamamoto et al. 2002) and resistance to bending loads  
 13 (Bonser and Ennos 1998). Several studies also attempted to evaluate tangential stress through the  
 14 released tangential maturation strains (RTMS), but this was always done in combination with  
 15 longitudinal stress, by releasing the stress in both directions (Jacobs 1945; Boyd 1950a; Kubler 1959;  
 16 Okuyama et al. 1981; Okuyama et al. 1994; Sasaki et al. 1978; Ferrand 1982b, 1982c). This  
 17 “bidirectional” stress release has strong consequences on the recorded strain values and their  
 18 relationship with *in-situ* stress, because of the mechanical coupling between the two directions, called  
 19 the Poisson’s effect.

20 This can be clarified by considering the case of a peripheral piece of wood in the standing tree that is  
 21 put in a state of longitudinal tension ( $\sigma_L > 0$ ) and tangential compression ( $\sigma_T < 0$ ) during maturation  
 22 (Fig. 1c). When the stress is released in only one direction (L or T), then the wood strains in the same  
 23 direction by an amount corresponding to the elastic response to an applied unidirectional stress  $-\sigma_L$   
 24 or  $-\sigma_T$ , while strain are impeded in the other direction:

$$25 \quad \alpha_L^L = -\sigma_L/E_L^* \quad \text{and} \quad \alpha_T^T = -\sigma_T/E_T^* \quad \text{Eq. (1)}$$

26 where  $\alpha_j^j$  is the strain in direction  $j$  in response to stress release the same direction, and  $E_j^* =$   
 27  $E_j(1 - \nu_{TL}\nu_{LT})$ , with  $E_j$  the elastic modulus of wood in direction  $j$ ,  $\nu_{TL}$  and  $\nu_{LT}$  the Poisson’s ratio,  
 28 related by  $\nu_{LT} = \nu_{TL} E_L/E_T$ . From these equations, it is clear that the strain released in one direction  
 29 is representative of the stress in the same direction. However, when the stress is simultaneously  
 30 released in both directions, then the wood strains as in a response to a bidirectional stress  $(-\sigma_L, -\sigma_T)$ :

$$31 \quad \alpha_L^{LT} = -\left(\frac{\sigma_L}{E_L} - \nu_{TL} \frac{\sigma_T}{E_T}\right) \approx \alpha_L^L - \nu_{TL} \alpha_T^T \quad \text{Eq. (2)}$$

1 
$$\alpha_T^{LT} = -\left(\frac{\sigma_T}{E_T} - \nu_{LT} \frac{\sigma_L}{E_L}\right) \approx \alpha_T^T - \nu_{LT} \alpha_L^L \quad \text{Eq. (3)}$$

2 where  $\alpha_j^{LT}$  are the strains in direction  $j$  in response to bidirectional stress release. These equations  
3 show that, for bidirectional stress release, the strain measured in one direction depends on the state of  
4 stress in both directions, *i.e.* the measurements contaminate each other as illustrated in Fig.1c.

5 In the case of angiosperm woods, the usual values for Poisson's ratio range between 0.02 and 0.05 for  
6  $\nu_{TL}$ , and between 0.3 and 0.6 for  $\nu_{LT}$  (Bergman et al. 2010). Therefore  $E_j^*$  and  $E_j$  differ by less than  
7 2%, so that the second member of eq. (2) and (3) are very good approximations. Moreover, it will be  
8 shown in this article that  $\alpha_L^L$  is several times larger in magnitude than  $\alpha_T^T$ . Therefore, it can be  
9 predicted that the contamination is negligible for the longitudinally released strain, *i.e.*  $\alpha_T^{LT} \approx \alpha_T^T$ ,  
10 while this contamination effect is dominant in the case of tangentially released strain: if bidirectional  
11 release is performed, then the strain recorded in the tangential direction strongly depends on the  
12 magnitude of longitudinal stress.

13 For this reason, in order to use released strains as an indicator of the *in situ* maturation stress, it is  
14 advisable to first perform the release of tangential stress by making longitudinal grooves, record  
15 unidirectionally released tangential maturation strain (RTMS), and then release the longitudinal stress  
16 by making tangential grooves to estimate the released longitudinal maturation strain (RLMS).

17 The aim of this paper is to apply this method to have precise estimates of both RTMS and RLMS in  
18 standing trees, and to assess the patterns of maturation stress in fast growing eucalyptus trees in  
19 relation to their growth rate and wood microstructure.

20

21

## 22 **Material and methods**

### 23 *Plant material*

24 Experiments were performed on 29 *Eucalyptus nitens* H. Deane & Maiden trees selected in a 12-  
25 years-old trial located in the region of Biobio in Chile. The stand density was 1390 stem/ha, with a  
26 mean tree height of 26.5 m and a dominant height of 34.7 m. Trees selected for the study included  
27 both straight and leaning trees with diameter at breast height ranging from 18 to 28 cm.

28

### 29 *Measurement of released strains*

30 Released maturation strains were measured both along T and L directions at 5 positions per tree  
31 around breast height, sometimes slightly above or below in order to avoid the vicinity of branches.

1 Position #1 was chosen on the upper side of the leaning trees, where reaction wood was expected, and  
2 randomly for straight trees, then position #2 and #5 were picked at 45° from position #1, and position  
3 #3 and #4 on the opposite side of position #5 and #2, respectively (see Fig. 2). This procedure was  
4 designed to make sure there were enough measurements in the tension wood areas of leaning trees.

5 The procedure for measuring released maturation strains along tangential (T) and longitudinal (L)  
6 directions consisted in several steps illustrated in figure 3. The bark was first removed and the  
7 cambium was peeled to ensure a correct gluing and a measurement on rigid wood. Then, biaxial strain  
8 gages 0°/90° stacked rosette (Kyowa) were pasted parallel to the grain at each measurement position,  
9 and connected to the data-logger. The data-logger was initialized at this stage. Tangential release was  
10 done by two longitudinal groves made with a sharp knife 5 to 8 mm away from the gage on both  
11 sides. Grove was 2 to 5 mm thick to enable full dilatation of tangentially compressed wood. They  
12 were performed successively on each measurement position. Then, longitudinal release was done by  
13 sawing tangentially above and below the gage at the same distance, successively on each  
14 measurement position. The data logger recorded the strain values of each gage during the whole  
15 procedure. Released strain was defined as the difference between the value recorded before the first  
16 grove at the first gage and the value recorded after the second grove of the fifth gage was completed  
17 in T direction. Similarly, in L direction, released strain was obtained from the difference between  
18 value read before the first sawing at first gage and the value read after the second sawing of the fifth  
19 gage.

#### 21 *Observation of wood anatomy*

22 At each measurement position, transverse sections (approx. 20 µm thick) were observed with a  
23 microscope to assess the presence of reaction wood. Double staining with safranin – astra blue was  
24 used to assess the presence of an unlignified gelatinous layer (G-layer), and the appearance and  
25 thickness of the cell-wall was observed.

#### 27 *Statistical analyses*

28 Statistical analyses were conducted using software Statistica®. Significance of linear correlations was  
29 tested with a Fisher test. The “tree” effect on measured variables was tested using one-way ANOVA.  
30 The analysis of relationships between variables while controlling for the “tree” effect was performed  
31 using general linear model. The level of significance of all tests was 5%.

1

2

### 3 **Results**

#### 4 *Effect of the stress release at a position on the strains at other positions*

5 Fig. 4 shows the L and T strains recorded at each position during the release performed in L and T  
6 directions at each position, on a representative tree. Fig. 4a shows the effect of T release on T strain,  
7 and illustrates that the release along T at position 1 (TRp1) not only released the strain at position 1  
8 (TSp1) but also affected the strain at other positions (TSp2,3,4,5) in a smaller amount. Similar effect  
9 was observed later for releases at following positions, so that the T strain at each position increases  
10 during successive stress T releases. This means that the longitudinal grooves made for tangential  
11 release at one position also affected the mechanical state of the entire cylinder. Fig. 4c shows that, in  
12 contrast, T release had a negligible effect on L strains at each position. Fig 4d shows that the release  
13 in the L direction at a given place influences L strains at other position in a negligible amount. Fig 4b  
14 shows that L release at a given position has a strong effect on the T strain at this position (due to the  
15 Poisson's effect), and a smaller, although non-negligible, effect on the T strain at other positions (see  
16 e.g. TSp5).

17

#### 18 *Effect of the release of longitudinal stress on the measured tangential strain*

19 Figures 5 shows the relationships between the T strain recorded after unidirectional T release (RTMS)  
20 and that recorded after bidirectional release in both T and L directions. The correlation between these  
21 variables is strongly significant ( $p < 10^{-6}$ ). However, when comparing to the 1:1 line, it is clear that  
22 tangential strain after bidirectional release greatly overestimates the RTMS. The slope of this  
23 relationship is more than 2, showing that the coupling effect is dominant with this measurement  
24 method. The Poisson's ratio can be evaluated from this relationship, based on eq. (3):  
25  $\nu_{LT} = (\alpha_T^T - \alpha_T^{LT}) / \alpha_L^L$ . With this method the estimated Poisson's ratio ranges between 0.2 and 0.5,  
26 which is consistent with usual values of this parameter.

27

#### 28 *Patterns of released longitudinal maturation strain (RLMS)*

29 All RLMS measured during this study were negative, meaning that L maturation stress was always  
30 tensile. The average magnitude of RLMS was 1382  $\mu$ strains ( $\pm 688$  S.D.). The overall variability of  
31 RLMS values was large, and more than half of it was due to a tree effect ( $R^2 = 0.57$ ,  $p < 10^{-6}$ ). Fig. 6 is a  
32 plot of the maximum RLMS versus the minimum RLMS measured on each tree. This figure enables

1 the visualisation of both the base stress level and the asymmetry of stress in each tree. If the  
2 maturation stress was uniform on a tree, it would be located on the diagonal; the vertical distance to  
3 the diagonal indicates the magnitude of asymmetry. Most trees present a significant asymmetry of  
4 stress and half of the trees have their maximum RLMS at least two times higher than their minimum  
5 RLMS (dots on the right hand of the dotted line in Fig. 6). Remarkably, some trees have minimum  
6 RLMS larger than the maximum of some others.

7

#### 8 *Released tangential maturation strain (RTMS)*

9 All RTMS measured during this study were positives, meaning that T maturation stress was always  
10 compressive. The average value of RTMS was 264  $\mu$ strains ( $\pm 124$  S.D.), i.e. approximately 5 times  
11 lower in magnitude than RLMS. ANOVA revealed that, similarly to RLMS, more than half of the  
12 variability was due to a tree effect ( $R^2=0.56$ ). A significant correlation was found between RTMS and  
13 RLMS: the higher the L tensile stress, the higher the T compressive stress (Fig. 7). This relationship  
14 was statistically significant when all observations were pooled together ( $R^2=0.32$ ,  $p<10^{-6}$ ) and was  
15 even stronger when the data were averaged for each individual tree ( $R^2=0.55$ ,  $p=0.04$ ). General linear  
16 model taking in account a “tree” effect showed that this relationship was close to be significant  
17 ( $p=0.067$ ) at the within-tree level.

18

#### 19 *Observation of wood anatomy*

20 Tension wood with typical G-layer was observed on 5 of the 29 trees (circled and numbered on fig.  
21 6). Trees 1, 2, 3, 4 were among the highest value of maximal RLMS. Trees 1 and 4 had G-layer at all  
22 positions around the circumference. Trees 2, 3 had G-layer only near the position of maximal RLMS.  
23 Tree 5 also had G-layer only near its position of maximal RLMS, but differed from trees 2 and 3 by  
24 its relatively low value of maximal RLMS. Nevertheless, we note that this tree had a comparatively  
25 high asymmetry (*i.e.* difference between maximal and minimal RLMS). In other trees, values of high  
26 RLMS were associated to a tension wood without G-layer, but instead a thick lignified secondary  
27 layer, distinctly thicker than opposite wood.

28

#### 29 *Maturation stresses and growth rate*

30 Previous results indicated that the maturation strains measured at the periphery of the trunk strongly  
31 depend on a tree effect: some trees clearly have large maturation stress all around their circumference.  
32 Analysis of the relationship between the mean released maturation strain on a tree and its diameter

1 reveals significant relationships ( $p < 0.001$  for both RLMS, Fig 8a, and RTMS, Fig. 8b). On even-aged  
2 plantation trees, this means that the lower the growth rate, the higher the magnitude of tensile RLMS  
3 and compressive RTMS. By contrast, the within-tree asymmetry of RLMS (quantified as the  
4 difference between maximal and minimal RLMS within each tree) was not significantly correlated  
5 with tree diameter.

6

## 7 **Discussion**

### 8 *Metrological considerations*

9 Our results show that, when tangential maturation strains are measured from bidirectional stress  
10 release ( $\alpha_T^{LT}$ ), the measurement is dominated by the strong coupling effect with longitudinal stress.  
11 These results are in agreement with theoretical considerations based on wood orthotropic behaviour,  
12 and their reliability is supported by the consistency of the values of Poisson's ratio  $\nu_{TL}$  estimated  
13 during the longitudinal stress release. This shows that, when attempting to measure both longitudinal  
14 and tangential maturation strains, it is necessary to perform the tangential release first and obtain the  
15 unidirectional tangential stress  $\alpha_T^T$ , as we did in this experiment, in order to have values representative  
16 and the *in situ* tangential stress.

17 Values of RTMS obtained from bidirectional stress release must be analysed with caution, because,  
18 generally, they provide a significant overestimation of the strains for normal and tension wood.  
19 Results obtained on samples taken out of the trunk (Ferrand 1982a) or wood disks (Boyd 1950a;  
20 Jacobs 1945; Kubler 1959) are basically bidirectional releases. The single-hole method is also based  
21 on a bidirectional release, although its interpretation does not rely on a simple Poisson effect but on  
22 complex stress redistribution around the hole. For compression wood, in which the longitudinal stress  
23 is compressive, negative tangential strains have been reported using a bidirectional release method  
24 (Yamamoto 1998), suggesting tensile stress, whereas the *in situ* stress is actually compressive. A  
25 posteriori correction of this Poisson's effect can also be used (Okuyama et al. 1994; Sasaki et al.  
26 1978), and data corrected with this method yield tangential strains of the same order of magnitude as  
27 our measurements. However this technique is less straightforward, needs more measurements (values  
28 of the Young's moduli and the Poisson's ratio obtained from laboratory tests) and the results can be  
29 very sensitive to the uncertainty of these additional measurements.

30 By contrast, using eq. (2) and the average values of  $\alpha_L^{LT}$ ,  $\alpha_T^T$  and  $\nu_{TL}$  obtained in this experiment, it  
31 can be shown that the difference between longitudinal strain after unidirectional ( $\alpha_L^L$ ) and  
32 bidirectional ( $\alpha_L^{LT}$ ) stress release is less than 1%. This means that the RLMS is almost unaffected by

1 the release of tangential stress. Therefore, most evaluations of longitudinal maturation stress that can  
2 be found in the literature can be considered as reliable, regardless of the fact that they were obtained  
3 from unidirectional or bidirectional stress release.

4 Our metrological analysis also showed that tangential strain can be significantly affected by the stress  
5 release performed in other locations of the tree. This is probably due to the complex stress  
6 redistribution that occurs when a free surface is created at one place. To address this issue, we advise  
7 to define the tangential released stress as the difference between the value read on the data logger  
8 before any groove is done on the tree, and the value obtained after the release of tangential stress at  
9 each position.

#### 11 *Magnitude and distribution of L maturation stress on plantation Eucalypt trees*

12 The RLMS recorded on plantation Eucalypt trees was always negative. No compressive value  
13 (positive released strain) was recorded as sometimes observed in the opposite wood of angiosperm  
14 trees (Clair et al. 2006a). The asymmetric patterns observed in most trees are consistent with  
15 expectation and usual observations (Fournier et al. 1994; Jullien et al. 2013; Nicholson 1973), as most  
16 trees are more or less mechanically imbalanced and need a gravitropic correction to maintain a  
17 vertical position (Alméras and Fournier 2009).

18 The average level of RLMS recorded in these trees was high (approx.  $-1380 \mu\text{strain}$ ) compared to  
19 usual value recorded on most species. This high level of longitudinal stress is however usual in  
20 eucalypt trees: in a study of *Eucalyptus* clones from Congo (Baillères et al. 1995), values very similar  
21 to ours are reported (average RLMS of  $-1300 \mu\text{strain}$ , maximal RLMS magnitude larger than  $-3500$   
22  $\mu\text{strain}$  (Gerard et al. 1995)). In another study on *E. nitens* in Chile (Biechele et al. 2009), average  
23 values of GSI (growth stress indicator measured with the single hole method (Gerard et al. 1995),  
24 which is correlated to RLMS (Fournier et al. 1994)) are found as high as 395 on 10-year-old  
25 plantation trees. For comparison, typical values of GSI are typically between 50 and 200 for beech  
26 (Fournier et al. 1994; Jullien et al. 2013) and chestnut (Fournier et al. 1994; Clair et al. 2003), as well  
27 as for various tropical rainforest species (Alméras et al. 2005), and lower than 150 for poplar  
28 (Alméras et al. 2005; Clair et al. 2006a). Studies by Nicholson (1973) also suggest the exceptionally  
29 high stress level of different species in the genus *Eucalyptus*.

30 For many trees, we recorded high values of RLMS all around the circumference, with a minimal  
31 value frequently larger than  $-1000 \mu\text{strains}$ . In some trees (e.g. tree 4 in fig. 6), this minimal value  
32 was as high as  $-1900 \mu\text{strains}$ , and not associated to a strong asymmetry. Nicholson (1973) also  
33 observed many eucalypt trees with high stress level all around their circumference. This pattern is

1 unusual: in most studies on other species, RLMS level is either low all around the circumference,  
2 revealing the absence of tension wood production, or presents high values of RLMS on only one side  
3 of the trunk, corresponding to an area of tension wood.

4 G-layer was observed only in some of the trees, and most of the time associated to the highest RLMS  
5 values. However, it was not observed at many positions where RLMS was more than 2000  $\mu$ strain,  
6 revealing the presence of tension wood without G-layer. The production of tension wood without G-  
7 layer is known to happen in many species (Clair et al. 2006b; Onaka 1949), showing that G-layer is  
8 not a necessary condition for the generation of maturation stress of high magnitude. This is  
9 particularly frequent in the genus *Eucalyptus* (Baillères et al. 1995; Scurfield 1972). We observed that  
10 *E. Nitens* produces tension wood both with G-layer and without G-layer. Nicholson (1973), suggests  
11 that on this species tension wood with G-layer is only an extreme manifestation of the ability to  
12 generate stress.

#### 14 *Tree effect and functional implications*

15 These results revealed an important “tree” effect on the distribution of maturation stress, here  
16 explaining more than half of the total variability for both RLMS and RTMS. Nicholson (1973) also  
17 observed this very important tree effect, with some trees having a high level of maturation stress all  
18 around their circumference. This tree effect was also present in a recent study on beech trees (Jullien  
19 et al. 2013), showing important coefficient of variation between trees of minimum and average RLMS  
20 levels. This shows that caution has to be taken when measurements from different trees are pooled  
21 together before analysis.

22 Moreover, from a functional viewpoint, this stress distribution cannot be explained just by the need of  
23 a gravitropic correction, since only the difference between the maximal and minimal maturation stress  
24 value is involved in this function (Alméras and Fournier 2009). This absence of gravitropic function  
25 of high stress levels has also been noticed by Nicholson (1973). Another function of longitudinal  
26 maturation stress is probably involved here: the improvement of the stem resistance against  
27 compressive failure during temporary bending loads such as wind (Bonser and Ennos 1998). This  
28 hypothesis is consistent with our observation that the mean level of maturation strain of a tree was  
29 correlated to its diameter. Although such a correlation was not detected by Nicholson (1973) in  
30 eucalypt, it has also observed on beech trees (Jullien et al 2013). This correlation can be interpreted  
31 through the fact that trees with smaller diameter have a lower bending stiffness due to their lower  
32 inertia, and are therefore probably more at risk regarding mechanical failure during wind loading.  
33 Tensile longitudinal pre-stress all around the circumference is an efficient way to reduce this risk.

1

2 *Growth stresses and tangential maturation stress*

3 The drawback for tree management is that these trees accumulate more longitudinal growth stresses.  
4 Moreover, because tensile longitudinal stress is correlated to compressive tangential stress, they also  
5 accumulate more transverse stresses. The correlation between L and T maturation stress as evaluated  
6 with our method is independent of the Poisson effect, but may be related to the mechanism of growth  
7 stress generation, that would produce lateral compression at the same time as longitudinal tension,  
8 consistently with the classical hypothesis explaining the generation of maturation stress in wood  
9 (Archer 1987).

10 The magnitude of released tangential strains was found about five times lower in average (260  
11  $\mu$ strains) than the longitudinal strain. This value is significantly lower than the figures reported in the  
12 literature when bidirectional release was used to evaluate tangential maturation strain: Jacobs (1945)  
13 reports values ranging from 800 to 4000  $\mu$ strain on various species, Boyd (1950a) values between 600  
14 and 1600  $\mu$ strain on 4 eucalypt species, and Kubler (1959) values between 1000 and 2600  $\mu$ strain on  
15 various species. In all these studies, the strain level is found the same order of magnitude as in  
16 longitudinal direction. However, in studies taking into account an *a posteriori* correction of the  
17 Poisson's effect, lower values are reported, closer to ours: a mean value of 760  $\mu$ strain for various  
18 broad-leave species (Sasaki et al. 1978), and 450  $\mu$ strain for normal wood of a conifer species  
19 (Okuyama et al. 1981).

20 The accumulation of elastic energy in the trunk during the development of growth stresses is very  
21 probably part of the cause of the frequency of log-end splits and heart checks observed in these  
22 populations. As explained by Kubler (1987), tangential compressive stress at the periphery implies a  
23 state of radial tension in the wood of the standing tree, which is maximal in the centre. Our results  
24 show that this stress is probably lower than previously predicted *in-situ* (Archer 1986). The major  
25 factor may be the indirect effect of the release of longitudinal stress due to the creation of a free  
26 surface when the tree is felled. This release of longitudinal stress tends to increase the state of tensile  
27 radial stress, for two reasons: (1) it has a direct effect on transverse stress through the material  
28 coupling effect (Poisson's ratio), so that the release of L compressive stress at the centre generates an  
29 important increment of radial tensile stress ; (2) in addition, a structural effect due to the strong  
30 longitudinal stress gradient (tensile at the periphery, compressive at the centre) tends to bend outward  
31 each "cake" of the section, adding significant transverse stress. Heart checks happen if the transverse  
32 stress becomes larger than the tensile strength of wood. Therefore log-end cracks are directly related

1 to the accumulation of growth stress during tree development, in response to its biomechanical need,  
2 although they are also dependent on other wood properties such as its toughness (Jullien et al. 2013).

#### 4 **Conclusions**

5 Based on careful measurements of released longitudinal and tangential maturation strains around the  
6 circumference of even-aged eucalypt plantation trees, our study leads to the main following  
7 conclusions:

- 8 • In order to evaluate released tangential strains in the standing tree, tangential stress has to be  
9 released before the longitudinal stress, to avoid a bias due to the dominant Poisson's effect
- 10 • All trees were in a state of tensile longitudinal stress and compressive tangential stress, the  
11 released strain being in average five times lower in magnitude in the tangential direction
- 12 • The higher the longitudinal tensile maturation stress, the larger the tangential compressive  
13 maturation stress
- 14 • Most trees exhibited an asymmetry of longitudinal stress around the circumference, which is  
15 interpreted as an adaption enabling to control their orientation
- 16 • More than half of the variability of maturation stress was found at a between-tree level, with  
17 many trees producing high longitudinal stress around their whole circumference
- 18 • High values of longitudinal stress are often observed even in absence G-layer, showing that  
19 the presence of G-layer is not a necessary condition for the production of high maturation  
20 stress in eucalypt
- 21 • The mean stress level of trees was negatively correlated to their diameter, which is interpreted  
22 as an adaptation improving their resistance against temporary bending loads such as wind

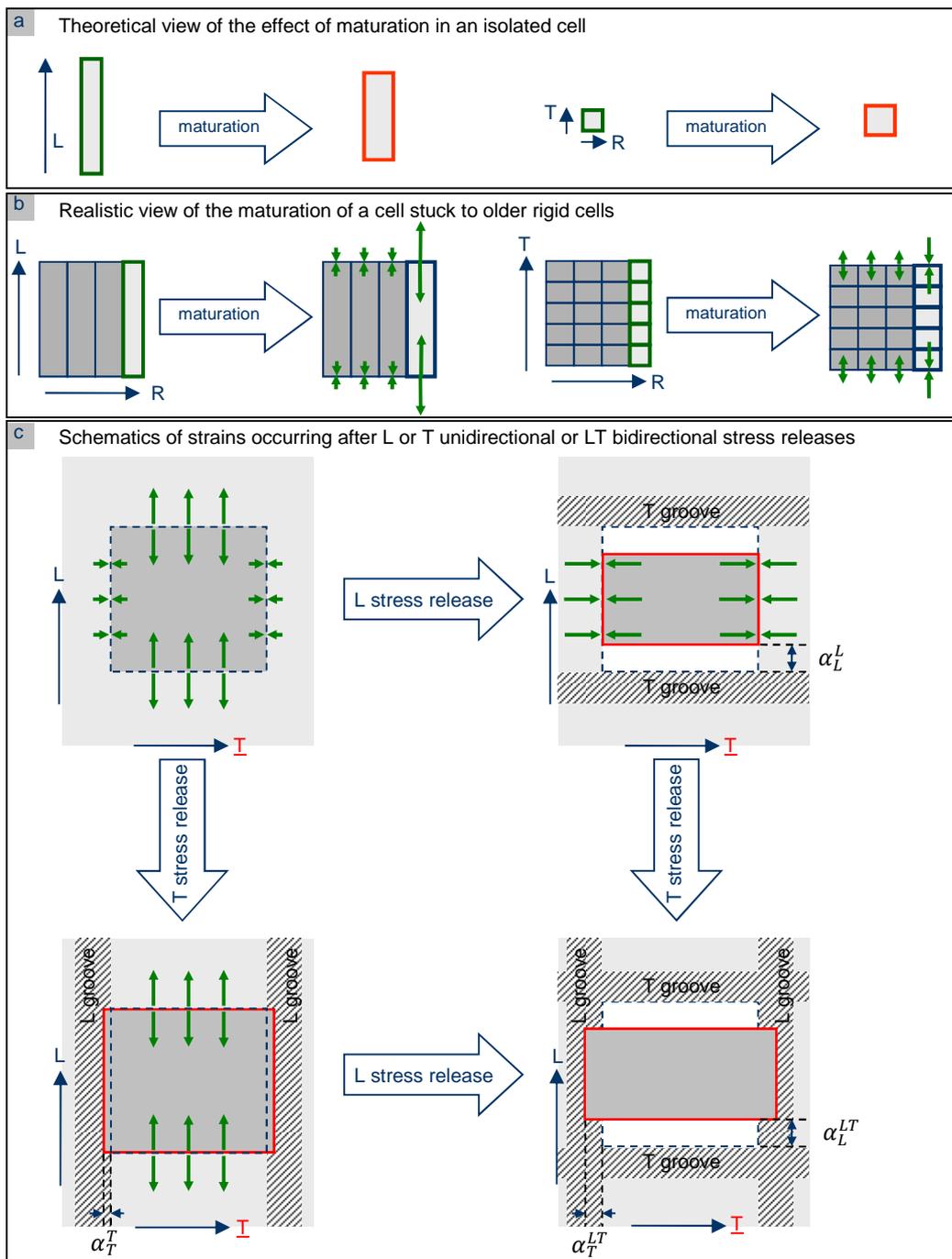
#### 24 **Acknowledgements**

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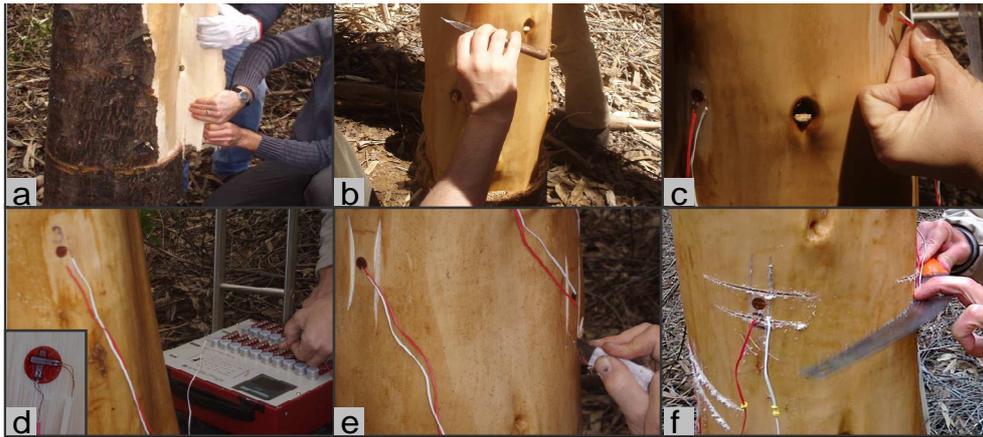


2 **Fig. 1.** Principle of the maturation stress generation and associated strains and stress in tangential (T) and  
 3 longitudinal (L) directions. Green cell: cell before maturation. **a:** red cell: theoretical view of the same cell after  
 4 maturation if it was isolated from other cells. **b:** blue cell: realistic view of the cell after maturation considering  
 5 that it sticks to older rigid cells. Green arrows represent maturation stress in the newly matured cell, and  
 6 growth stress increments that happen in the older cells in response to the maturation stress. Convergent arrows  
 7 figure a state of compression, divergent arrows a state of tension. **c:** Schematics of strains occurring after T or L  
 8 unidirectional or LT bidirectional release of maturation stress induced by making grooves in the wood. The  
 9 dashed blue rectangle represents the dimension of the measurement area at initial state, and the solid red

1 rectangle its dimension after stress release. Strains are figured with blue arrows (their magnitude is amplified for  
2 the purpose of representation).  
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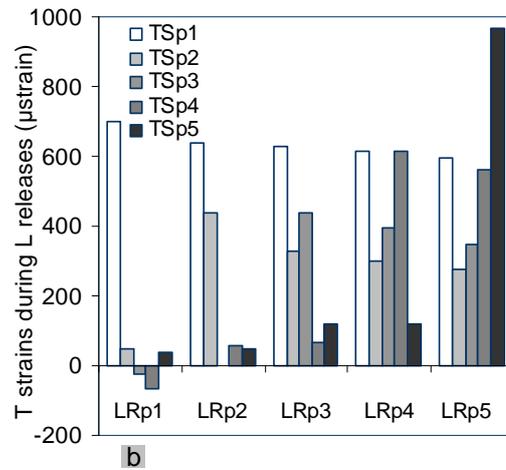
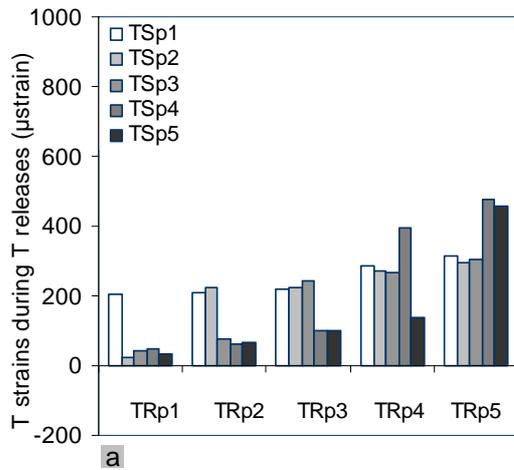
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5 **Fig. 2.** Example of a butt log cross-section picture showing strain gage locations (numbered 1-5), and cracks in  
6 the centre of the log observed few minutes after felling the tree  
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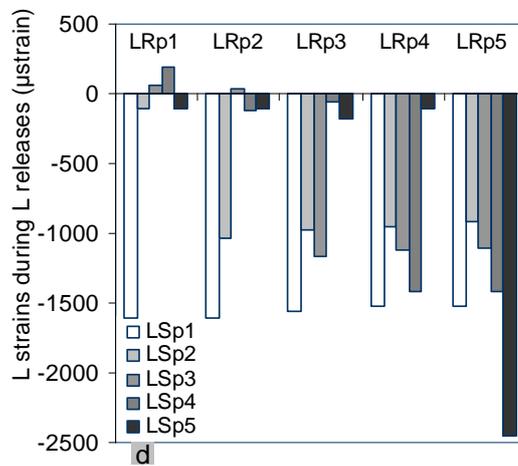
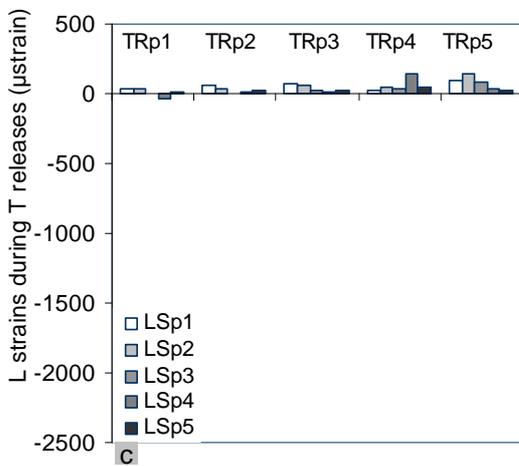
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**Fig. 3.** Step by step procedure for measurement of released maturation strains along tangential (T) and longitudinal (L) directions. **a:** remove the bark; **b:** peel the cambium; **c:** paste the gages along the grain (detailed in d); **d:** connect to data-logger and initialize; **e:** release along T with two grooves on both sides of each gage; **f:** release along L by sawing above and below each gage.

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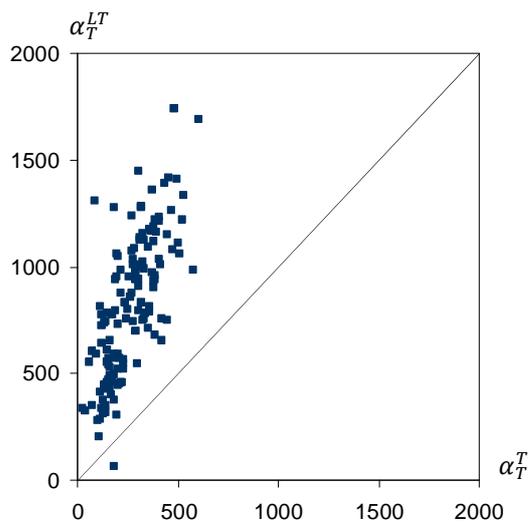
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**Fig. 4.** Example, on one of the trees, of the strains recorded along T and L at each position during the release along T and L at each position.  $TSp_i$  ( $LSp_i$ ): tangential (longitudinal) strain at position  $i$ ;  $TRp_i$  ( $LRp_i$ ) tangential (longitudinal) release at position  $i$ . **a:** T strain during release along T; **b:** T strain during the release along L; **c:** L strain during the release along T; **d:** L strain during the release along L.

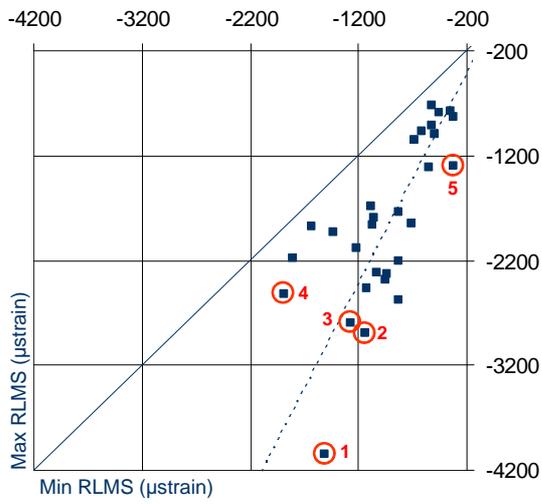


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2 **Fig. 5.** Relationship between the tangential strain after unidirectional release ( $\alpha_T^T$ ) and after bidirectional release  
3 ( $\alpha_T^{LT}$ ). Strains are expressed in microstrains ( $\mu\text{m/m}$ ). Regression slope: 2.07,  $R^2=0.53$ ,  $p<10^{-6}$ . Diagonal line  
4 indicates  $y=x$ .

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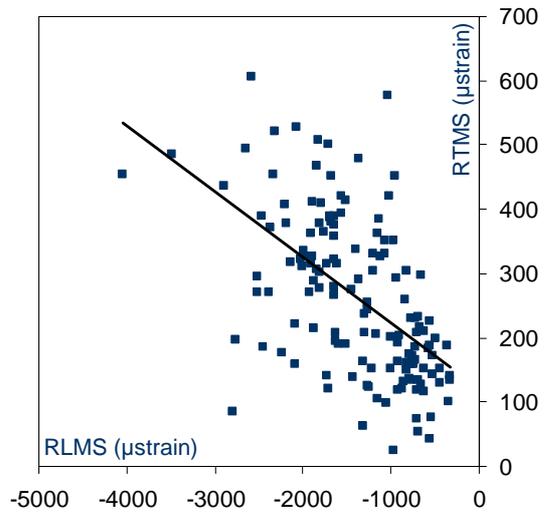


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3 **Fig 6.** Plot of the maximum versus the minimum released longitudinal maturation strain (RLMS) measured  
4 around each tree. Each dot is one tree. The vertical distance to the diagonal indicates the asymmetry of the  
5 RLMS around the tree. Dotted line separates trees with maximum RLMS at least 2 times higher than their  
6 minimum. Circles indicate trees where G-layer was found.

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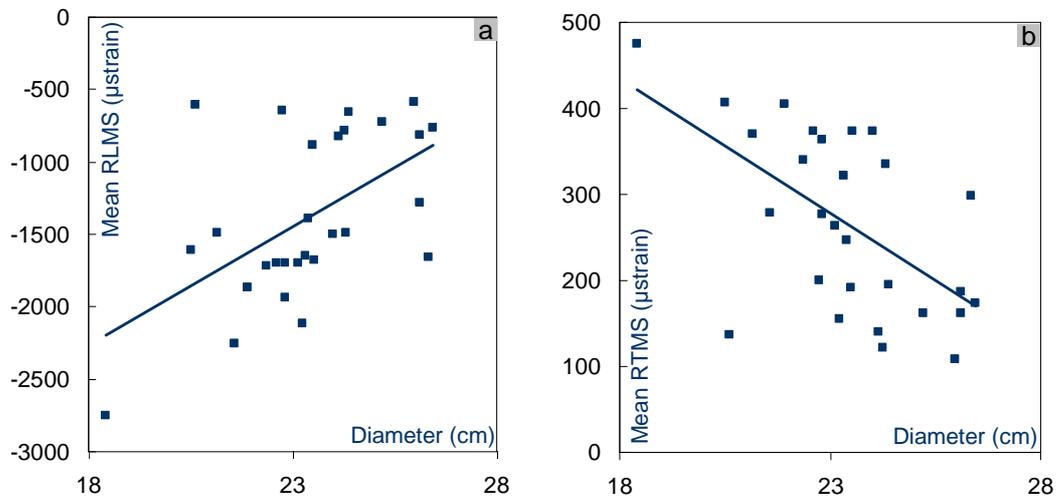
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**Fig. 7.** Relationship between released tangential maturation strain (RTMS) and released longitudinal maturation strain (RLMS) at all measured position. The correlation is statistically strongly significant ( $R^2=0.32$ ,  $p<10^{-6}$ ).

1



2

3 **Fig. 8.** Relationships between mean maturation strains and tree diameter. Each dot is the mean over one tree.

4 **a:** longitudinal maturation strain (RLMS),  $R^2=0.30$ ,  $P<0.001$ . **b:** released tangential maturation strain (RTMS) ,

5  $R^2=0.34$ ,  $P<0.001$ .

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