

Article

Effect of Stem Diameter, Genetics, and Wood Properties on Stem Cracking in Norway Spruce

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Abstract: The choice of seed material (genetics) is one of the tools that can improve adaptation to the changing climate. Insufficient adaptation can result in a number of potential risks, including stem cracking. The goal of this study is to assess the influence of genetics and wood properties on stem cracking in Norway spruce (*Picea abies* Karst). The study was conducted on a 35-year-old provenance trial in Eastern Latvia. Stem cracks were assessed using a six-score scale. Tree-ring parameters, i.e., latewood proportion, maximum and mean density, mean earlywood, and latewood density were analysed. The overall incidence of stem cracking was 23.5%, varying between 0% and 79% at a family mean level. Heritability of stem cracking was low, ca., two times lower than for the diameter at breast height (DBH): $h^2 = 0.09$ and 0.21 , respectively. There were non-significant family and provenance effects on the occurrence of stem cracks, and weak family mean correlations between DBH, and the proportion of trees with any stem cracks or severe stem cracks. Overall, larger trees were more prone to cracking irrespective of provenance or family. Cracked trees had lower wood density parameters than unaffected trees, yet the latewood proportion was similar. Silvicultural treatments or selection to improve wood density could be suggested to reduce the risk of stem cracking.

Keywords: stem scars; stem defects; heritability; wood density

1. Introduction

Norway spruce is economically important, compared to other forest trees and fast-growing tree species, and it covers extensive areas of the Baltic Sea region [1,2]. A high rate of survival and reduced risks of damage are essential to ensure the financial viability of the increasing investments in regeneration (primarily planting), especially while using genetically improved seedlots [3–5]. Therefore, not only high-volume production and timber quality, but also adaptive traits, are important breeding objectives [6,7]. The use of tree breeding results are expected to be an important tool for the adaptation of forestry to climatic changes [8]. In the region studied, the most pronounced effects of these are longer vegetation seasons and milder winters, as well as prolonged drought periods during the summer [9].

Prolonged drought periods are the probable triggering factor of stem cracks in Norway spruce. Tension inside the tracheid increases with an increasing water deficit until cell collapse occurs; when hydrostatic tension in the tracheids exceed the fracture limits of the middle lamella, and cracks occur [10–12]. The cracks are usually longitudinal, up to several meters long, and radially reach into the stem [10]. Sometimes cracks can be closed and appear as scars, with stained black coverage [13].

These obviously decrease timber quality, and trees with such open wounds in the stem are more prone to fungal infections [14–16].

Cracks may be a symptom of insufficient adaptation [10], and they have been observed in sample plots in the National Forest Inventory, also in Latvia [17]. Yet, there is a lack of detailed analysis linking the occurrence of cracks with wood properties. In recent decades, stem cracking in Norway spruce has been reported in Fennoscandia, especially on 15–35 year old plantations on former agricultural land, and originating from transferred reproductive material [10,13,18,19]. Also, in Latvia, geographically distant provenances demonstrated a significantly different frequency of trees with cracks [20]. However, there remains a lack of information on family-level genetic variations and the heritability of stem cracks needed for consideration in tree breeding. In addition, only one study has reported information on this important stem defect in the Baltic States [20]. It is important to both raise awareness of this potentially increasing problem, as well as improve the understanding of it in the context of potential adaptation measures. Therefore, the goal of the study is to assess the influence of genetics and wood properties on stem cracking in Norway spruce.

2. Materials and Methods

2.1. Studied Trial and Measurements

The assessed Norway spruce provenance trial was located in the eastern part of Latvia (56°39' N, 25°54' E), established in 1985 on former agricultural land with four-year-old bare-rooted plants with an initial density of 3333 stems ha⁻¹ (2 × 1.5 m). The mean annual temperature in the location was +6.0 °C; the mean monthly temperature ranged from –6.4 °C in February to +17.1 °C in July. The mean annual precipitation was ca. 700 mm [21]. The trial consisted of six local provenances (the locations of the sources from which the reproductive material was collected) from the southeast area of Latvia, with a known family structure (Table 1). A randomized complete block design was used with five blocks and 10 trees per plot. In 1995, systematic thinning had been done, retaining approximately 1600 stems ha⁻¹.

The diameter at breast height (DBH) was measured on each living tree in the summer of 2016. Height was impossible to measure due to a very high stand density. Stem cracks were assessed using a six-score scale according to methodology by Zeltiņš et al. [20]. Score 0 was assigned to trees without visible cracks or scars. Score 1 was assigned to trees with bark cracks that were a few centimetres long and shallow, not reaching the wood. Score 2 characterized a shallow crack in the bark up to ca. 1 m. Moderate damage (Score 3) was a crack in the bark and reached the wood, or closed scars from 1 to 2 m long with stained black coverage. Severe damage (Score 4) was a deep crack in the wood and scars with stained black coverage longer than 2 m. Very severe damage (Score 5) was assigned to trees with one or more open stem cracks that were several meters long, which reached radially deep into the stem [20].

In autumn, 2016, 5 mm increment cores at breast height were randomly collected from 17 trees with severe to very severe damage (Scores 4 or 5), and 17 controlled undamaged trees (Score 0). Only straight trees without visible crown asymmetry and other stem defects like root-rot, double tops, severe browsing damage, etc., were chosen. The increment cores were processed using high-frequency densitometry with the LignoStation wood analysis system, which utilizes the dielectric properties of wood [22]. For each sample core, ring width, latewood width, mean, earlywood, latewood, and maximum density were measured, and the proportion of latewood (latewood width/tree-ring width) was calculated and further used as an integrative parameter for both ring and latewood widths.

Table 1. Overview of the material used in the trial (SD—standard deviation).

Provenance	Geographic Coordinates	No of Families	No of Trees with Cracking Score						Mean Diameter at Breast Height \pm SD (cm)		Incidence of Stem Cracks (%)
			0	1	2	3	4	5	without Stem Cracks	with Stem Cracks	
Bērzgale	56°36' N, 27°30' E	26	210	20	12	13	12	7	18.2 \pm 4.63	19.8 \pm 5.66	23.4
Dagda	56°6' N, 27°30' E	29	263	31	16	14	2	6	18.1 \pm 4.08	18.2 \pm 4.82	20.8
Janopole	56°23' N, 27°18' E	26	178	16	19	12	8	14	18.2 \pm 4.33	20.7 \pm 4.68	27.9
Kalsnava	55°42' N, 26°41' E	24	227	17	18	10	8	12	17.9 \pm 4.06	19.1 \pm 4.57	22.3
Kalupe	56°6' N, 26°30' E	24	202	18	15	8	11	15	17.9 \pm 4.05	18.8 \pm 4.60	24.9
Silene	56°42' N, 25°53' E	23	202	22	10	10	5	13	18.2 \pm 4.47	19.9 \pm 4.72	22.9
Total		152	1282	124	90	67	46	67	18.1 \pm 4.27	19.4 \pm 4.84	23.5

2.2. Data Analysis

Variance and covariance components for the genetic analysis were estimated using the SAS[®] Mixed procedure (PROC MIX) (SAS Institute, Cary, NC, USA) with a restricted maximum likelihood approach for analysing the DBH and the generalized linear mixed procedure (PROC GLIMMIX) (SAS Institute, Cary, NC, USA), applying a cumulative logit link function for analysing the stem cracking score. The following analytical model was used:

$$y_{ijkl} = \mu + B_i + P_j + F_{k(j)} + BF_{ik(j)} + e_{ijkl} \quad (1)$$

where y_{ijkl} is the observation of stem cracks on the l th tree from the k th family within the j th provenance in the i th block; μ is the general mean; B_i and P_j are the fixed effects of the i th block and the j th provenance, respectively. The $F_{k(j)}$ is the random effect of the k th family within the j th provenance, and $BF_{ik(j)}$ is the random interaction effect of the i th block, and the k th family within the j th provenance (plot effect). e_{ijkl} is the random residual effect. The significance of the random factors was estimated with Wald Z tests, based on the estimates and asymptotic standard errors in the SAS output.

Estimates of narrow-sense individual tree heritability (h^2) and family mean heritability (h_f^2) were obtained for DBH and stem cracking variance components from the analytical model described above. For stem cracking, the environmental variance $\hat{\sigma}_e^2$ was fixed to be $\pi^2/3 = 3.29$ [23]. The individual tree heritability was calculated as [24]:

$$h^2 = \frac{4 \times \hat{\sigma}_f^2}{\hat{\sigma}_f^2 + \hat{\sigma}_{fb}^2 + \hat{\sigma}_e^2} \quad (2)$$

where $\hat{\sigma}_f^2$, $\hat{\sigma}_{fb}^2$, and $\hat{\sigma}_e^2$ are the estimated variance components of the family, family \times block interaction, and the residual, respectively. The Family mean heritability was calculated using the formula [24]:

$$h_f^2 = \frac{\hat{\sigma}_f^2}{\hat{\sigma}_f^2 + \frac{\hat{\sigma}_{fb}^2}{b} + \frac{\hat{\sigma}_e^2}{bn}} \quad (3)$$

where b is the number of blocks and n is the number of trees per plot.

The effects of DBH and DBH \times provenance interaction on the severity (score) of stem cracks were assessed by a mixed model:

$$y_{ijkl} = \mu + D_{ijkl} + PD_{ijkl} + B_i + F_{k(j)} + BF_{ik(j)} + e_{ijkl} \quad (4)$$

where D_{ijkl} and PD_{ijkl} are the fixed effects of the DBH of the l th tree from the k th family within the j th seedlot in the i th block, and the provenance \times DBH interaction. B_i and $F_{k(j)}$ are the random effects of the block, and the k th family within the j th provenance, and $BF_{ik(j)}$ is the random interaction effect of the i th block and the k th family within the j th provenance, and e_{ijkl} is the random residual effect. The ordinal logistic function was applied using R package ordinal [25]. Pearson correlation analyses based on family mean observations was used to quantify the association between the DBH and the incidence of trees with stem cracks (score > 0), and the incidence of trees with severe stem cracks (Score 4 and 5).

For the increment cores, the measured time series were cross-dated and verified by a graphical inspection and statistically using the program COFECHA [26], as described by [27]. The tree ring parameters between the core samples with and without cracks were compared by a t -test. The calculations were done in an R software environment for statistical computing [28].

3. Results

3.1. Effect of DBH and Genetics

The trial mean DBH \pm standard deviation (SD) was 18.4 ± 4.44 cm. The overall incidence of stem cracks was 23.5% (Table 1). The provenance mean incidence of stem cracks varied from ca. 22% to 28% (Table 1), and family mean varied from 0% to 78.6% (Figure 1). Long stem cracks or scars up to several meters were observed. The family mean proportion of trees with the largest cracks (Score 4 and 5), ranged from 0% to 50%, and was on average 6.7%. The DBH was a significant factor ($p < 0.01$), determining the incidence of stem cracks of any severity, yet the interaction effect of provenance \times DBH was insignificant ($p = 0.08$). Thus, within each of the provenances, faster-growing trees were more greatly affected.

Neither provenance nor family were a significant factor ($p = 0.37$ and $p = 0.16$, respectively) affecting the occurrence of stem cracks, while the block had a significant impact ($p = 0.01$). However, trees with stem cracks did not tend to occur in clusters. The estimated family variance formed a small proportion of phenotypic variance, resulting in a rather low individual-tree heritability $h^2_i \pm$ standard error (SE) = 0.09 ± 0.091 , as well as family mean heritability $h^2_{fam} \pm$ SE = 0.20 ± 0.206 (Table 2). Individual tree and family mean heritabilities (\pm SE) for DBH were 0.21 ± 0.088 and 0.31 ± 0.128 , respectively.

Based on family means (152 families), no clear tendency for a genetic relationship was observed between family mean DBH and (a) the incidence of stem cracks (Score > 0) within a family ($r = 0.028$, $p = 0.75$), or (b) the incidence of severe cracks (Score 4 and 5) within a family ($r = 0.059$, $p = 0.50$) (Figure 1). Thereby, severely cracking trees were among families with a small as well as large mean DBH.

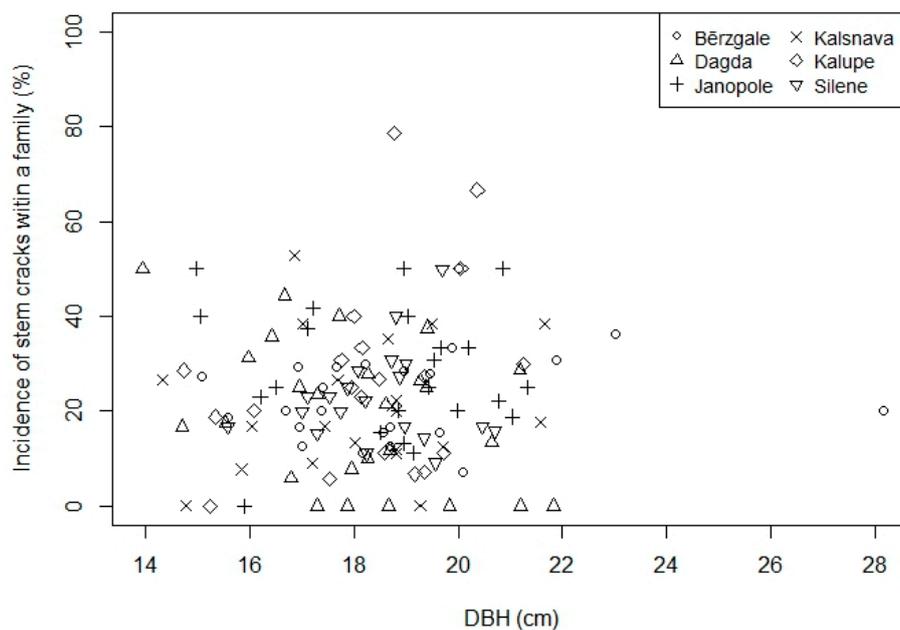


Figure 1. Differences in diameter at breast height (DBH) and the incidence of stem cracks among families.

Table 2. Estimated variance and covariance components and heritability for stem cracking.

Component	Estimate (Standard Error)
Additive genetic (family) variance	0.074 (0.077)
Variance of additive genetic variance	0.006
Family \times block variance	0.013 (0.130)
Environmental variance	3.29
Individual-tree narrow sense heritability	0.088 (0.091)
Family mean heritability	0.198 (0.206)

3.2. Tree-Ring Analysis

Core samples from severely cracked trees (Score 4 and 5) had a significantly lower wood density ($p < 0.01$) than unaffected trees (Table 3). For cracked trees, the maximum, mean, mean earlywood, and mean latewood densities were 8.9%, 17.0%, 17.0%, and 8.4%, respectively, and they were lower for unaffected trees. However, the latewood proportion did not differ ($p = 0.97$) between either group of sample trees (Table 3).

Comparing the tree-ring parameters on an annual basis showed mostly negligible differences occurred in any given year between both groups of trees (Figure 2). For the mean density, the most notable differences were during the period of 2010–2015, when cracked trees had a significantly lower mean density than the unaffected samples in the years 2013–2015 (Figure 2). Earlywood density tended to be higher for undamaged trees during all observation periods, though significant differences were estimated only within individual years.

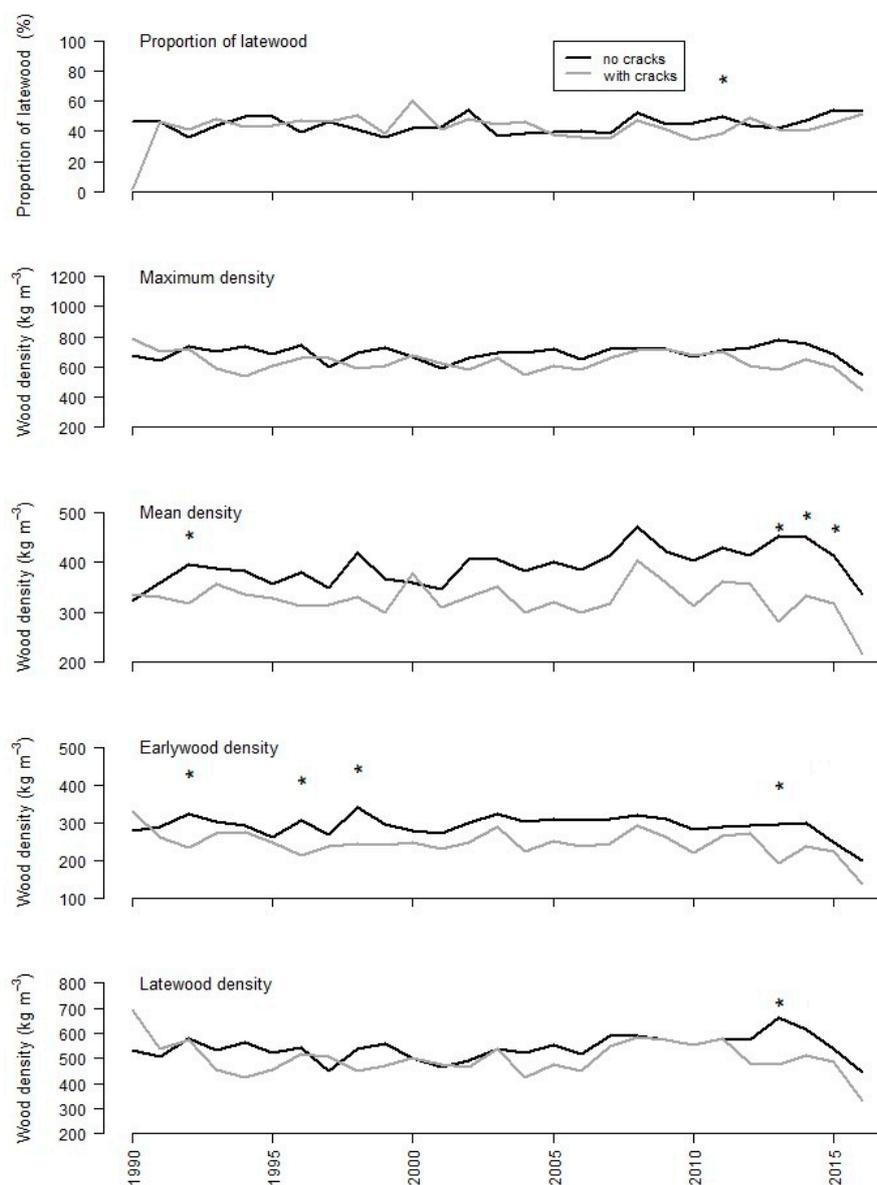


Figure 2. Mean measurement time series of four analysed Norway spruce groups (* denote significant differences ($p \leq 0.05$) between trees with and without cracks).

Table 3. Statistics of tree-ring parameters (MIN = minimum, MAX = maximum, MEAN = mean values, SD = standard deviation, DIFF = *p* values of differences in mean values of mean time series of the tree-ring parameters of the two analysed groups).

	MIN	MAX	MEAN	SD	DIFF
Latewood proportion					
no cracks	0.36	0.54	0.44	0.05	
cracks	0.34	0.60	0.44	0.06	0.79
Maximum density (kg m ⁻³)					
no cracks	594	783	696	45.4	
cracks	539	716	633	53.0	<0.01
Mean density (kg m ⁻³)					
no cracks	345	471	398	32.9	
cracks	282	402	330	27.4	<0.01
Mean earlywood density (kg m ⁻³)					
no cracks	250	341	297	21.0	
cracks	194	292	247	23.6	<0.01
Mean latewood density (kg m ⁻³)					
no cracks	449	661	547	46.0	
cracks	422	586	501	49.6	<0.01

4. Discussion

At the study site, the frequency of cracked stems (23.5%) was higher than was reported in earlier studies. The incidence of stem cracks in the IUFRO 1964/68 series was 7% for Bjerkøy (Norway) and 2% for Abild (Sweden) [13]. In the Swedish combined clonal and seedling seed orchard, around 4% of the trees showed cracking [29]. In Lithuania, the frequencies of 36-year-old trees with scars and cracks in the seed orchard were 10.9% and 14.8%, respectively [14]. In the 15–30-year-old provenance trials, located in Norway, the frequency of cracked stems varied from 0% to 20.3% [10]. In two 41–44-year-old contiguous provenance trials in Western Latvia, 31% of trees with stem cracks were reported [20]. Yet, most of the damage (28% of all trees) was light cracks in the bark, believed not to affect wood properties primarily and considerably, contrary to the observed severely damaged (Scores 4 and 5) trees (ca. 7%), with cracks that were several meters long at the present study site.

More frequent severe stem cracks among larger trees indicated a potential risk for Norway spruce plantations with fast radial growth, which is further supported by the results of earlier studies in the region [10,13,14,30]. In this study site, the forest type corresponded to the fertile *Oxalidos*. Earlier studies suggest that fast growing spruce plantations on abandoned agricultural land, planted with wide spacing, are most vulnerable to cracking [10,13,29,31]. On rocky forest soil, cracks tend to occur less frequently [19]. However, in the studied trial, the initial spacing of 1.5 × 2 m and the density was kept high until the moment of inspection, due to the lack of frequent thinning.

In spite of the dense stand, the frequency of cracked stems was relatively high, indicating the importance of other factors (fertile soil and/or extreme climatic events in the past) influencing the growth of trees and enhancing stem cracking. No positive correlation between stem dimensions and the frequency of stem cracks and/or wounds has been found in Finland, where severe cracks appeared across the whole DBH spectrum [19]. We found no evidence to confirm the conclusions [10], that trees under a certain DBH do not crack, and that “as a rule there is only one crack at a given height.” At the study site, a number of trees with two or three severe cracks at the same height (Score 5) were found.

Clear tendency toward a higher frequency of stem cracks in provenances with rapid growth had been highlighted [32]. In Norway, more stem cracks were reported in fast-growing spruce proveniences than among slow growing ones [10]. The same pattern was observed in southern Sweden, where provenance mean DBH was correlated ($r = 0.74$) with the incidence of stem cracks, which varied from 1% for provenances with the smallest DBH to ~10% for fast growing provenances

with the largest mean DBH [13]. The provenance was also reported to have a significant effect on stem cracking in western Latvia [20].

Nevertheless, similar to a Swedish study [33], no significant difference in the frequency of stem cracking among provenances was observed. The provenance differences could be masked due to a high stand density, which might have a restricted radial growth potential for different provenances, thus reducing the expression of stem cracks. Moreover, in earlier studies, the variance among provenances was more pronounced due to long transfer distances and subsequent maladaptation [10,13,20,32,34], while our study site consisted of local eastern Latvian seedlots.

Still, the variation within a provenance may sometimes be large, as among geographically distant origins [2]. For local southeast Latvian provenances, the incidence of stem cracks within a family was not related to the family mean DBH (Figure 1). Within one provenance, the families with no cracks, as well as the ones with a ca. 79% incidence of stem cracks, could be found (Figure 1).

The estimated individual tree heritability for stem cracking score was low, and only 8.8% of phenotypic variances in the trial could be explained by an additive genetic variance. An estimated h^2 for DBH was ca. two times higher. High (0.45–0.57) broad-sense heritability for internal cracking was reported in clonal trials [30]. Still, the estimated family mean heritability was higher and it showed that ca. 20% of the phenotypic variance of stem cracking could be controlled with selection, based on half-sib progeny tests.

Nevertheless, a complex analysis of different sites would provide a more reliable view, since heritabilities for productivity and quality traits may vary widely from low to high, depending on the site [30,35,36].

Tree-Ring Analysis

Trees with stem cracks were reported to have wider annual rings with a small latewood proportion, which led to wood with a high proportion of earlywood and subsequent poor strength and low density due to thin cell walls and delayed lignification [10,13]. Earlier studies indicated a clear negative correlation between basic density and annual ring width, and a positive relationship between basic density and cell wall thickness [12,32,37,38].

Thin-walled earlywood cells with low basic density are more susceptible to collapse, which might explain more frequent cracking of larger trees having a higher proportion of earlywood than thick-walled latewood, in which lower tangential stresses could be expected [39]. In this study, the proportion of latewood shows a negligible difference among groups of cracked and unaffected samples. However, earlywood, as well as latewood density, was by ca. 50 kg m^{-3} lower (Table 3) for samples with cracks compared to undamaged wood, indicating a lower mechanical resistance, which might have promoted the induction of cracks [12].

Lower density for cracked trees correspond to earlier findings, indicating the importance of selection for less susceptible wood with higher density than excluding the cracking itself [13]. Control of earlywood density in breeding programs is suggested [12], as it is reported to have moderate to high broad-sense heritability (0.33–0.51) [30]. In addition, for vegetative propagation, the selection of appropriate clones should take into account the tree predisposition to stem cracking.

5. Conclusions

Larger trees with reduced wood density parameters were more prone to stem cracking. Likely caused by climatic factors, the manifestation of cracking had rather weak genetic control, as shown by non-significant family and provenance effects, though family mean heritability indicated a potential for selection based on progeny tests to reduce the incidence of cracks. There was no evidence of reduced latewood proportion for affected trees, though the exclusion of genotypes, with reduced wood density during breeding activities, may help to avoid trees prone to stem cracking.

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