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Longitudinal stem cracks in larch: what makes trees vulnerable?

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Abstract
Stem cracks are becoming a major problem affecting timber quality and its economic value; their frequency may increase with increasing frequency and severity of drought stress due to climate change. Several major conifer species are affected, but such damage was mentioned for the first time in France for hybrid larch (*Larix x eurolepis*) in 1993. Even though a link was made with severe drought some years ago, it was believed, at that time, that the rapid growth of hybrids might be the cause. Our study is intended to disentangle the role of growth versus drought in the appearance of cracks, based on observations in two field genetic trials. Summer drought was clearly identified as the main trigger of longitudinal cracks. Roughly 5–15 years of age seems to be the critical period during which the occurrence of most of the cracks was observed. Wood formed during this period corresponds to juvenile wood, well-known for its weaknesses. Nevertheless, some trees escaped cracking damage: compared to trees with cracks, these looked slender (higher HD ratio), had wider rings and greater grain angle in the early years but similar wood density. Fast growth has often been cited as enhancing crack occurrence. This conclusion is corroborated by our observations that, within a given variety or family, trees with cracks were consistently larger than trees without cracks. Nevertheless, this conclusion should be qualified by the additional observation that, across varieties/families, the faster growing material were not necessarily the most prone to cracks, highlighting the crucial role of the genetic background of the material planted.

Keywords *Larix* · Hybrid · Crack · Drought · Ring · Density · Spiral grain angle · Growth

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Introduction

Stem cracking has long been known in conifers (e.g. Day (1950) who studied this phenomenon after a severe drought in Wales and Scotland in 1947), but the number of papers on stem cracks has significantly increased since the beginning of the 1980s. Norway spruce (*Picea abies* (L.) H.Karst.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (Day 1954; Dietrichson et al 1985; Monchaux and Nepveu, 1986), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Polge 1982, 1984) and grand fir (*Abies grandis* (Douglas ex D. Don) Lindley) (Langlet 1985; Boulet-Gercourt and Nepveu 1988) seem to be particularly susceptible, but some other species also suffer, including noble fir (*Abies procera* Rehder) (Barrett 1958) and some pines (Hungerford 1973; Ball et al. 2001). For the first time in France, Cazaux et al. (1993) reported observations of stem cracks in hybrid larch (*Larix x eurolepis* Henry) following the 1990 summer drought. From then on, we have regularly observed stem cracks in the genetic trials managed by INRAE of European (*Larix decidua* Mill.) and Japanese (*L. kaempferi* (Lamb.) Carr.) larches and their hybrid.

According to species, at least two main types of cracks are recognized: the first type concerns small, internal, diamond-shaped cracks, occurring at ring level and not visible from the outside; the second type is usually long longitudinal cracks visible from the outside, often deep and extending radially from pith to bark. Both types are frequent, for example in spruces, and may even coexist in the same tree (Hungerford 1973). However, there is little evidence of a connection between the two types. It seems from our observations that larch is mostly affected by the second type even though internal cracks have also been reported by Appel (1980). For both types, drought (in summer), often associated with high temperatures, is clearly identified as the main cause (e.g. Persson 1994; Grabner et al. 2006; Rosner et al. 2018), so that one can talk of '*drought-cracking*'. With climate change and more frequent and severe periods of drought, it is expected that the frequency of stem cracks in stands will increase (Cameron 2019).

Besides differential species propensity to cracking, genetic differences in susceptibility to cracking among either provenances or clones have been noted by some authors (Dietrichson et al. 1985; Persson 1994; Vasiliauskas et al. 2001) but not by others (Eriksson et al. 1975; Zeltins et al. 2018). Among other factors, some soil characteristics have been reported to increase the risk of cracking: either by reducing soil water reserves, linked to depth and texture (Cameron 2019), or by enhancing growth through, for example, soil fertility (Kohler et al. 2018). Wide spacing (Persson 1994) and any silvicultural treatment reducing tree HD ratio (Kohler et al. 2018) may also favour cracking.

Internal tension within the wood in connection with drought stress has been suggested as the origin of cracks. Various authors have investigated weakness in some wood properties in order to test this hypothesis. Using pairs of trees of similar sizes and often with microdensity analysis, they analysed ring characteristics for size, density, proportion of latewood, and grain angle. Although a general consensus has been reached with respect to wood density: cracks occur more frequently in trees with a lower density (Day 1954; Boulet-Gercourt and Nepveu 1988; Monchaux and Nepveu 1986; Persson 1994; Zelnis et al. 2018), many contradictory results are reported for other traits (ring width, proportion of early/latewood). Results are probably species- and variety/family -dependent but some confusion may arise from the generic name used to qualify this defect ('crack') under which at least two different realities exist: small internal and long longitudinal cracks.

Fast growing trees have been identified as more susceptible to cracks by several authors (e.g. Persson 1994; Vasiliauskas et al. 2001; Kohler et al. 2018; Cameron 2019). Among

temperate conifers, larch is one of the fastest growing species (Da Ronch et al. 2016). Thanks to hybridization, hybrids (*Larix x eurolepis*) between European (EL) and Japanese larches (JL) express superior growth over their parent species across a wide range of sites (Pâques et al. 2013; Greenwood et al. 2015; Marchal et al. 2017); this is further enhanced in plantations, which usually have more favourable conditions and are more intensively managed than in the native range of the parent species. For that reason, when Cazaux et al. (1993) observed cracks for the first time in France in hybrid larch, they hypothesized that this stem defect might be caused by the rapid growth of the hybrid and they called them '*growth-cracks*'. Their network (17 sites across France) included only one hybrid commercial variety (FP203DK) and they could not relate the frequency of cracks to environmental factors. So, doubt about the origin of cracks persisted and questions about the susceptibility of hybrid larch in general remained open.

In this study, we attempted to disentangle the role of growth vs drought in the occurrence of cracks in larch; in particular, we wanted to investigate how ring properties differ between trees with and without cracks. For this purpose, we used two genetic field trials, allowing us to study the variability of sensitivity to cracks at species and different genetic levels.

Material and methods

Field trials

Trial 1: variety trial

The first trial is a variety trial comprising six hybrid larch varieties produced in commercial European seed orchards: namely Barres (F), FP201 (DK), FP203 (DK), FP205 (DK), FP211 (DK) and Halle (B). These seed orchards include from 1 to 12 inter-mixed parent clones from each species and commercial seed lots are obtained through open-pollination of one or rarely both species. Commercial seedlots were sown and raised as stock plants in the nursery. Two years later, in spring 1992, seedlings of all six varieties were 'bulk' vegetatively propagated by cuttings, using 20 cm-long explants, typically used in our nursery (and referred to as 'Normal cuttings'). In addition, for four of the six varieties, 4–5 cm-long explants were also used for comparison (referred to as 'Micro-cuttings'). The main advantage of 'Bulk' propagation is to allow mass-production of a variety while conserving its intrinsic genetic diversity. Bare-root rooted cuttings (850) were then planted at spacings of 3×3 m at St-Julien-Le-Petit (Haute-Vienne; Latitude 45°49′N, Longitude 1°42′E, Altitude 460 m) in April 1995. Each treatment (variety x type of cuttings) was represented by 30–60 plants distributed in two blocks with plots of 15–30 plants. Prior to this study, the stand was never thinned.

The site is on an 11% slope (locally 24%) with a westerly aspect. The plantation is on a shallow sandy soil with around 20% clay and with a water reserve estimated to be less than 50 mm. The climate is oceanic and theoretically favourable for larch planting, with a mean temperature of 11.2 °C and precipitation reaching 1182 mm (595 mm from April to September) (Meteo-France 1998–2010, Eymoutiers climatic station). Nevertheless, during recent decades several summer droughts have occurred with particularly low precipitation between June and August (e.g. 2003, 2005, 2016) (Fig. 1 upper left) as well as with

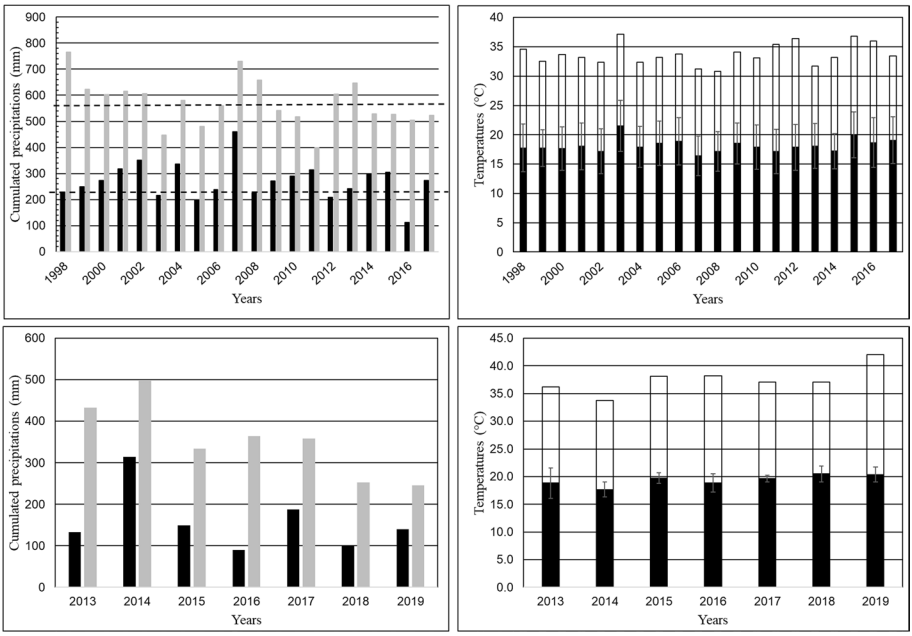


Fig. 1 Climatic parameters for *Trial 1* (top) and *Trial 2* (bottom): Left: cumulated precipitation over years from June to August (black bars) and from April to September (grey bars); Right: mean temperatures of summer months (June to August) over years (black bars) and maximal daily temperatures monitored during that period (empty bars)

extreme daily maximal summer temperatures (> 35 °C in 2003 but also in 2011, 2012 et 2015) (Fig. 1 upper right).

Trial 2: diallel progeny trial

The second trial is a subset of a 9 EL + 9 JL diallel mating design including intra- and inter-specific crosses. Connected pedigrees from 12 full-sib families for each of the three species (EL, JL and HL), each represented by 10–11 individuals, were compared. Each individual was clonally propagated by grafting in 2011 to obtain six ramets per individual (clone). Ramets of each clone (1900 plants in total) were planted at spacings of 3 × 2.5 m at the INRAE nursery in Orléans (Loiret; Latitude 47°49′55″ N; Longitude 1°54′50″ E; Altitude 109 m) in spring 2013. They were nearly equally distributed between two plots subjected to contrasting water regimes. Within each plot, families and ramets of clones were randomly distributed following an incomplete randomized block design with 10 blocks and single-tree plots. Within each block, clones of each species were kept separate. One plot received continuous daily drip-irrigation from April to October, the other was without irrigation.

The site was chosen for its high drought stress propensity due to climate (mean precipitation: 642.5 mm; April-September: 318.8 mm; mean temperature: 11.3 °C; Meteo-France 1981–2010; Orléans climatic station) and exacerbated by the gravel and coarse sand texture of its soil (former bed of the Loire river).

The years 2018 and 2019 were characterized by the driest growing seasons with less than 253 mm of rain (mean: 355 mm); 2016 and 2018 had the driest June–August period

since planting (Fig. 1 lower left). In addition, 2018 and 2019 had the highest summer mean temperatures (Fig. 1 lower right). Records of daily maximum temperatures were met for June and July 2019, reaching 38.1 °C and 42 °C respectively, and for August 2018 and 2016 (37.1 °C and 38.2 °C respectively).

Measurements and observations

In *trial 1*, the first measurements of total height (H) and girth at breast height (BH) were collected at the end of 2005. At that time, a high frequency of stem cracks was observed, probably due to the 2003 summer drought. Presence/absence of cracks was recorded. Trees were measured and observed a second time in 2018 prior to thinning.

In *trial 2*, tree growth (total height and BH diameter) has been yearly monitored since the plantation was established and the impact of any abiotic events (e.g. drought, frost, wind) recorded. Stem cracks were observed for the first time in 2018.

HD ratio was calculated using directly measured BH diameter (*trial 2*) or diameter estimated from BH girth assuming the trunk is a cylinder (*trial 1*).

Sampling for the wood property study

In *trial 1*, twenty-two pairs of trees of similar vigour with and without cracks were chosen from four varieties (FP201, FP203, FP205 and FP211) so as to cover the whole range of crack frequency observed at variety level. Choice of trees was restricted to trees in plots obtained from normal cuttings. Five to six trees with visible cracks were first identified within each variety plot and an equivalent number of the nearest trees without cracks but of similar vigour, supposedly occupying the same micro-environment, were used for the analysis.

Each tree was marked to indicate the north-facing side; in September 2018, that is 24 years after plantation establishment, trees were felled. Additional measurements included the heights at the start and end of cracks as well as their orientation.

From each tree, a 1.5 m long basal log was sawn together with a 15 cm thick wood disk sampled at the middle of the crack length (*sample 1*) for further dating of the crack. From the basal log, a 10 cm thick disk (*sample 2*) was sawn at around 1.3 m and used for preparation of microdensity samples. From the remaining part of the log, a 5 cm thick board centred on the pith was sawn. From it, a 35 mm thick sample without visible defect was prepared for analysis of spiral grain angle (*sample 3*).

Measurements on samples (Fig. 2)

Sample 1 disks were used for dating cracks. Following cracking, tissues of the next ring are associated with healing and more or less rapidly cover the crack. Thus, the ring preceding this healing corresponds to the ring when cracking appears.

From sample 2 disks, 2.5 mm thick, 10 mm wide diametrical boards were sawn and kept at room temperature for several weeks. Boards were then X-rayed. Ring limits were determined using Windendro (version 20008e Regent instruments Canada inc.; http://www.regent.qc.ca/products/dendro/DENDRO.html) software and with R (R core team 2021, version 4.1.2) scripts developed by INRAE, we further processed density profiles to calculate

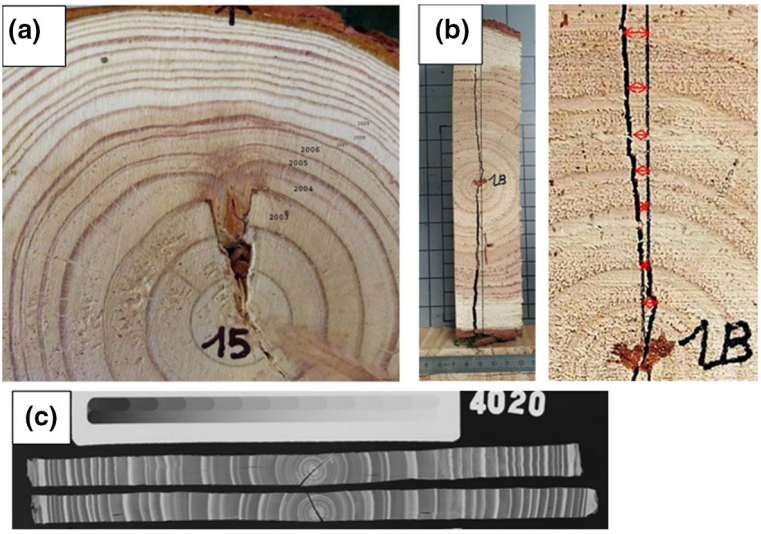


Fig. 2 a Dating of the crack: healing started in 2004 right after cracking in 2003; b Measurement of spiral grain angle after sample splitting and measurement of the distance between the split line and the reference line at annual ring limits; c X-rayed samples ready for microdensitometric analysis

ring width, early- and latewood width, mean ring density and early- and latewood density as well as minimal and maximal densities.

Sample 3 sections were used to measure spiral grain angle following Nakagawa's protocol (1972) (*in* Fujimoto et al. 2006). Two parallel base lines passing through the pith were drawn on each cross-section of the sample. With a sharp metal blade applied on the same upper face for all samples, disks were split and their lower face was scanned. Using Image J (version 1.46r) software, the distance (D, mm) between the base line and the crack was measured at the latewood limit of each ring. Knowing the thickness of the sample (E, mm), the grain angle (ANG, in degrees) for each ring at both radii was calculated as

$$ANG = \arctan\left(\frac{D}{E}\right)$$

According to the position of the crack relative to the base line, angle is considered either positive or negative. Spiral grain values at each ring were expressed as the mean of absolute values of the two measurements at the two opposite radii. The mean spiral grain at a given ring was calculated as the mean of all angles up to that ring.

Statistical analysis

For *trial 1*, the first analysis aimed at testing whether significant differences existed between varieties (*trial 1*) with respect to frequency of cracks. A generalized linear mixed procedure (GLM R), applying a logit link function, was applied and odds ratios were tested if significantly different from 1.

$$Y_{ijkl} = \mu + Var_i + CType_j + Bl_k + \varepsilon_{ijkl} \quad (1)$$

where Y_{ijkl} = binomial variable (presence/absence); Var_i = variety; $\mathrm{CType_j}$ = cutting type; Bl_k = block; ε_{ijkl} = residual.

In order to test whether there were differences with respect to growth traits and HD ratio between trees with and without cracks, an analysis of variance was conducted for each variety following the model

$$Y_{ijk} = \mu + F_i + Bl_j + \varepsilon_{ijk} \tag{2}$$

where F_i = type of tree (with or without cracks); Bl_j = block and ε_{ijk} = residual.

Links between frequency of cracks and growth parameters, HD and mortality at mean variety plot level were investigated using Spearman correlation coefficients (r_S).

To compare sampled trees, with and without cracks, for differences in ring properties (width and density) and grain angle, a two-way analysis of variance was used following the model

$$Y_{ijk} = \mu + P_i + F_j + \varepsilon_{ijk} \tag{3}$$

where P_i = pairs of trees of similar size, F_j = type of tree (with or without cracks) and ε_{ijk} = residual.

For *trial 2*, we used a similar model as (1) to test for differences between species and water regime treatments in relation to stem cracks

$$Y_{ijkl} = \mu + Spe_i + Tr_j + Bl_{k(j)} + \varepsilon_{ijkl} \tag{4}$$

where Y_{ijkl} = binomial variable (presence/absence); Spe_i = species; Tr_j = water regime treatment (irrigated, non-irrigated); $Bl_{k(j)}$ = block/water regime treatment; ε_{ijkl} = residual. *Bl* was finally discarded from model (4) because of its strong collinearity with *Tr* (VIF > 1, vif R).

To test whether the water regime treatments had a different impact on crack frequency at the individual family level, the Fisher exact test was implemented on 2 by 2 tables of count data using the Fisher.exact function (exact2 × 2 R package). This test is well suited to small sample sizes and unbalanced data.

Results

Description of cracks (from trees sampled in trial 1)

As 'crack' is a generic term with different meanings, we start here with a short description of the cracks found in this study. For most of the 22 trees sampled with cracks in *trial 1*, the crack reached the pith and clearly occurred in 2003 with visible healing as soon as 2004 (Fig. 3, left). For two trees, up to 2003, there was no trace of cracking, only necrosis of the cambium followed by healing the following year (Fig. 3, right). For one tree, the crack recorded in 2005 was no longer visible in 2018. Half of the cracks developed on the southern side of the trees (11 trees out of 22); others were found on the western side (4 trees) or the northern side (5 trees) and none on the eastern side. One half of the cracks looked mostly vertical while the other half developed a left-handed spirality. Cracks appeared at a mean height of around 4.1 m (2.2–5.8 m), i.e. in the lower third of total height in 2018. They were, on average, 65.8 cm long: the shortest were 20 cm long and the longest exceeded 120 cm. Vertical cracks were usually smaller than the left-handed ones (respectively 48.5 vs 84.9 cm on average). Based on microdensitometric data, we estimated the

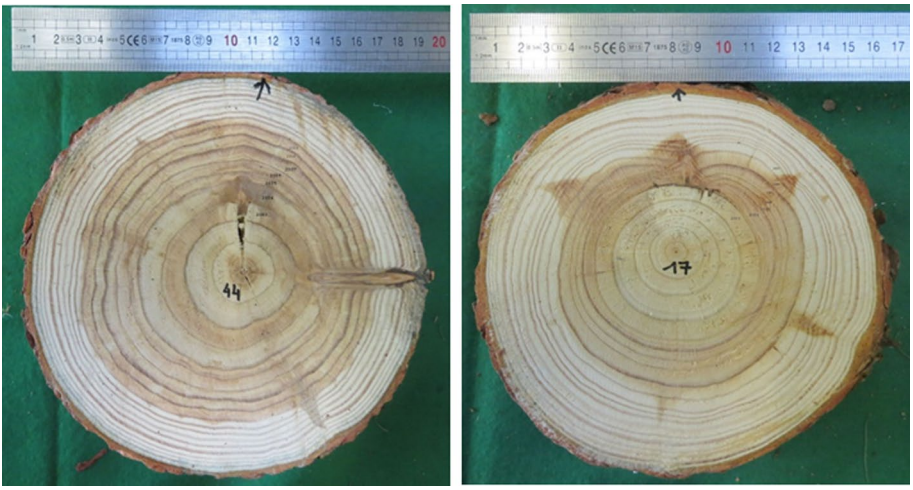


Fig. 3 Left: tree with a crack that appeared in 2003 with complete healing in 2004; Right: tree with cambium necrosis in 2003 and the start of healing in 2004

mean BH diameter over bark in 2003 to be equal to 9.3 cm (4.6—14.4 cm),—the percentage of bark was estimated following Thill and Palm (1984) as 16% of BH girth. In 2018, all cracks had been closed as a result of healing.

Frequency of cracks and link with growth

In *trial 1*, ten years after plantation establishment, we observed that the proportion of trees with cracks exceeded 57%. The statistical model showed highly significant variety and cutting type effects (Pr (> Chi) = 6.731e-10 and 0.0007 respectively) but no block effect ((Pr (> Chi) = 0.753). High variability among varieties was observed, with extreme values at around 20% for FP211 and 70% for Barres (Table 1). Cutting type also had a strong influence on the frequency of cracks (Table 2): trees from micro-cuttings were significantly less affected than those from normal cuttings, with 32.9% of stems

Table 1 Proportion of trees with cracking per variety and mean characteristics of trees in 2005 with and without cracking (*trial 1*): HT is for total height and HD is height/diameter ratio

Variety	Frequency of crack (%)	*p* value odds ratios	Mortality rate (%)	BH Girth (mm)		HT (cm)		HD	
				Without	With	Without	With	Without	With
BARRES	70.0	0.840	5.5	**356.1**[1)]	**443.3**	**838.5**	**957.2**	**76.6**	**68.3**
FP201	64.1	0.910	13.3	**342.9**	**458.7**	**833.9**	**956.3**	**80.7**	**65.9**
FP203	61.8	0.789	31.3	**333.0**	**449.7**	**749.3**	**826.0**	**75.9**	**60.1**
FP205	43.1	0.022*	19.1	402.0	423.9	882.0	901.6	70.3	67.0
FP211	20.4	4.904e-07***	6.9	**410.0**	**498.5**	1026.4	1095.8	**81.9**	**70.3**
HALLE	32.3	0.001**	27.0	**352.2**	**477.1**	801.6	873.0	**75.5**	**58.6**

1)Figures in bold indicate significant differences between trees with and without crack ($p < 0.05$)

* significant at 5%, ** significant at 1%, *** significant at 0.1%

Table 2 Proportion of trees with cracking per variety and type of cutting (Normal and Micro cuttings) and mean characteristics of trees in 2005 (*trial 1*): HT is for total height and HD is height/diameter ratio

Variety	Frequency of crack (%)		BH Girth (mm)		HT (cm)		HD	
	Normal	Micro	Normal	Micro	Normal	Micro	Normal	Micro
FP201	78.6	27.3	433.9	374.5	928.0	863.1	71.1	71.9
FP203	69.0	38.5	417.9	364.0	776.8	818.3	64.3	73.5
FP205	46.2	35.0	418.7	391.3	900.7	861.6	68.5	70.4
HALLE	31.8	33.3	416.5	345.5	872.6	753.3	68.4	73.7
Cutting type	53.3	32.9	422.9	369.4	904.7	824.0	69.5	72.3
p value odds ratios	0.0007***		22.364	3.36e-06***	22.537	3.34e-06***	2.812	0.0947 ns
F test and *p* value								

ns not significant, *** significant at 0.1%

with cracks compared to 53.3% for normal cuttings (p value odds ratio < 0.001). The distribution of affected trees across the plantation looked mostly homogeneous.

Focusing on trees obtained from normal cuttings only, odds ratios (OR) significantly higher than 1 were found for Barres (OR = 2.602, p value = 0.044) and significantly lower than 1 for FP205, FP211 and Halle (OR = 0.367, 0.200 and 0.109 (p value = 0.011 , < 0.001, < 0.0001) respectively).

We observed no link between crack proportion and mortality rate ($r_S = 0.074$, p value = 0.82): for example, varieties with the highest (Barres) and the lowest (FP211) proportions of cracked trees both had the highest survival. The mean vigour of the varieties did not seem to influence the proportion of defects ($r_S = -0.259$ and 0.371 with p values = 0.417 and 0.237 respectively for HT and girth). For example, both FP211, the most vigorous, and Halle, the least vigorous, had the lowest proportions of cracks (Table 1). However, trees with cracks were systematically the most vigorous ($p < 0.05$) and had a lower HD ratio.

Considering the four varieties involved in the two types of vegetative propagation (normal and micro-cutting), we observed (Table 2) that trees from normal cuttings were more affected by cracks and were also significantly the most vigorous compared to trees from micro-cuttings (BH girth = 422.9 compared to 369.4 mm; HT = 904.7 compared to 824.0 cm) and with a lower but not significantly different HD.

In 2018, no new trees with cracks were observed.

In *trial 2*, cracks were observed for the first time in 2018, which was 6 yrs after plantation establishment; fewer than ten additional cracks were recorded in 2019. At that time, trees had a mean diameter of 7.4 cm [4.5–12.6 cm]. The frequency of trees affected remained negligible (1.1%) in the irrigated plot whereas it reached 14.4% in the non-irrigated plot (Table 3) in 2019. Hybrid and Japanese larches were the most susceptible (> 16%) and European larch the least affected (10.3%). Only European larch had an odds ratio significantly lower than 1.

Moreover, as shown in Table 4, a wide variability in susceptibility to cracking was observed among families within species: in the non-irrigated plot, frequencies ranged

Table 3 Proportion of stems with and without cracks per species and per water regime (*trial 2*) *p* values are for odds ratios and indicate if these ratios are significantly different from 1

	2018						2019					
	Irrigated			Non-irrigated			Irrigated			Non-irrigated		
	n	%	*p* value	n	%	*p* value	n	%	*p* value	n	%	*p* value
EL	279	1.4	$<2^e{-}16$	182	8.29	$<2^e{-}16$	278	2.5	$<2^e{-}16$	155	10.3	$<2^e{-}16$
HL	311	1.0	0.944	222	12.2	0.064	312	1.0	0.610	176	16.5	0.058
JL	286	0.0	0.992	176	10.2	0.662	284	0.0	0.991	126	16.7	0.234

EL European larch, *JL* Japanese larch and *HL* hybrid larch

from 0 to 28.6%, 0 to 54.5% and (0) to 37.5% for EL, HL and JL respectively. With only three exceptions, families in the irrigated plot overall had a lower frequency of cracks (between 0 and 14.8%) than in the non-irrigated plot (between 0 and 54.5%).

Overall, Hybrid and Japanese larches, with the highest proportion of trees with cracking (Table 5), had a significantly (p value <0.05) higher mean diameter (respectively 73.7 ± 20 mm and 68.0 ± 21.6 mm for hybrid and Japanese larches) than European larch (58.7 ± 19 mm), but their mean HD ratio did not differ. More interestingly within each species, it can be seen in Table 5 that trees with cracks had a significantly larger diameter (p value <0.001) and lower HD ratio than trees without cracks. For HD, the differences were significant (p value <0.05) for JL and HL, but not for EL.

Comparison of wood properties of sampled trees with and without cracks (trial 1)

Ring width

As shown in Fig. 4 (left), trees with cracking had consistently wider mean annual ring widths and earlywood widths than trees without cracking up to 2003, with a peak in 2002. Indeed, during this period, ring width reached, on average, 6.1 (± 1.2) and 7.0 (± 1.3) mm for total ring width and 4.9 (± 1.0) and 5.7 (± 1.0) for earlywood width for trees without and with cracks respectively. Differences in ring width were significant in 1998 and from 2000 to 2003 (p value <0.05). After this date, the ring width of trees with cracks became smaller or of similar size to those of trees without cracks: 3.2 mm (± 1.5) compared to 3.5 (± 1.7) for total ring width and 2.4 mm (± 1.2) compared to 2.7 mm (± 1.3) for earlywood width. For latewood, mean ring sizes of trees with cracks were either smaller or larger from an early age but did not differ significantly from trees without cracks. During the 1998–2003 period, mean latewood percentage varied between 12.1 and 25.5% and did not differ significantly between the two types of trees, except in 1999. When looking at the evolution of cumulated growth over years (Fig. 4 right), it is apparent that a greater difference in ring size between trees with and without cracking was observed in 2003 (difference highly significant: $p<0.001$).

Ring density

Mean ring density over years as well as early- and late-wood densities were not significantly different between trees with cracks (0.433 ± 0.038; 0.339 ± 0.030; 0.723 ± 0.077 g/dm^3 for

Table 4 Family proportion of stems with cracks in irrigated (IRR) and non-irrigated (NIRR) plots and *p* value for Fisher exact test of differences between water regimes

Species	Family	Water regime				Fisher. exact test
		n	NIRR	n	IRR	(*p* value)
EL	104×106	19	15.8	28	3.6	0.289
	104×109	16	12.5	28	0.0	0.127
	104×214	13	7.7	27	0.0	0.325
	104×221	15	13.3	27	3.7	0.287
	104×284	16	0.0	28	3.6	1.000
	106×109	14	28.6	25	0.0	0.012
	106×166	9	11.1	22	0.0	0.290
	106×221	10	0.0	19	0.0	1.000
	106×222	14	0.0	26	0.0	1.000
	106×242	17	5.9	27	14.8	0.634
	106×284	10	10.0	18	0.0	0.357
	(109×222)	2	50.0	3	0.0	0.400
HL	104×3190	13	0.0	28	0.0	1.000
	104×3193	14	0.0	29	0.0	1.000
	104×3194	17	11.8	26	0.0	0.151
	104×3200	17	11.8	29	0.0	0.131
	106×3190	15	0.0	29	10.3	0.540
	106×3193	15	6.7	22	0.0	0.405
	106×3194	17	17.6	28	0.0	0.048
	106×3200	15	33.3	25	0.0	0.005
	221×3194	12	8.3	22	0.0	0.353
	221×3200	14	21.4	19	0.0	0.067
	222×3194	11	54.5	24	0.0	0.000
	222×3200	16	37.5	31	0.0	0.001
JL	3179×3194	14	14.3	29	0.0	0.101
	3179×3200	8	25.0	29	0.0	0.042
	(3180×3190)	2	0.0	2	0.0	1.000
	(3180×3193)	3	0.0	7	0.0	1.000
	3180×3194	13	7.7	26	0.0	0.333
	3180×3200	8	37.5	21	0.0	0.015
	3183×3194	14	21.4	27	0.0	0.034
	3183×3200	12	16.7	27	0.0	0.089
	3194×3203	14	28.6	33	0.0	0.006
	3194×3217	14	7.1	26	0.0	0.350
	3200×3203	14	14.3	27	0.0	0.111
	3200×3217	10	10.0	30	0.0	0.250
EL		177	9.6	330	2.1	< 0.001
HL		176	16.5	312	1.0	< 0.001
JL		143	14.0	330	0.0	< 0.001

n number of trees observed, *EL* European larch, *JL* Japanese larch and *HL* hybrid larch

Table 5 Mean characteristics of species and trees with and without cracks for BH diameter (DBH) and HD ratio in 2019 (*trial 2; non-irrigated plot only*)

	Mean (SD)	1)	Without	With	*p* value
DBH (mm)					
EL	58.7 (19.0)	c	56.2	82.4	< 0.001
HL	73.7 (20.0)	a	70.8	88.6	< 0.001
JL	68.0 (21.6)	b	64.4	90.0	< 0.001
HD					
EL	80.5 (26.3)	a	81.3	72.3	0.177
HL	78.0 (12.9)	a	79.2	71.7	0.004
JL	76.9 (23.4)	a	78.5	66.9	0.038

EL European larch, *JL* Japanese larch and *HL* hybrid larch

1) Different letters indicate that significant differences exist among species ($p \leq 0.05$)

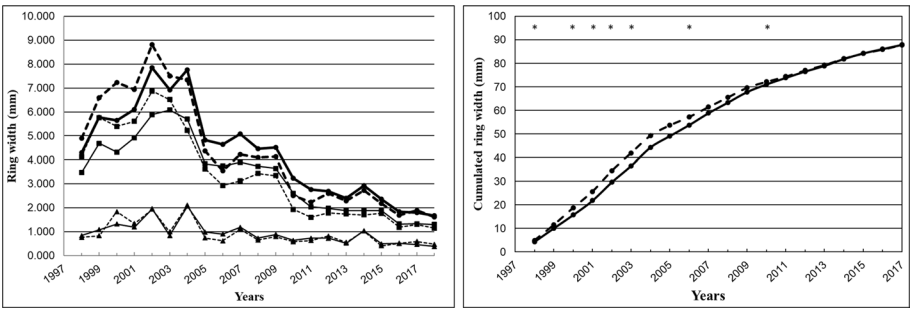


Fig. 4 Left: Evolution of mean annual ring width (Filled circle), and of early- (Filled square) and late-wood (Filled triangle) widths over years for trees without (solid line) and with (dotted line) cracks (*indicates years when significant differences ($p < 0.05$) were observed between trees with and without cracks for ring and earlywood widths). Right: cumulated ring width for trees with (dotted line) and without (solid line) cracks

ring, early- and late-wood respectively) and without cracks (0.425 ± 0.030; 0.338 ± 0.026; 0.712 ± 0.078 g/dm^3) (Fig. 5). Maximum and minimum ring densities showed the same results (not presented).

It is noteworthy that the ring formed in 2003—that is when cracks appeared—is characterized by the lowest mean density observed (< 0.37 g/dm^3), corresponding to a parallel decrease in both early- and latewood densities.

Spiral grain angle

Figure 6 shows the evolution of the mean grain angle along annual rings for trees with and without cracks. For trees with cracks, the angle was, on average, smaller than that of trees without cracks, or was similar the early years following plantation establishment, but from 2003 onwards, the angle became systematically greater. Analysis of variance indicated significant differences between pairs of trees ($F_{obs} = 30.901$, $p < 0.001$, df: 20, 863) and between individuals with and without cracks ($F_{obs} = 9.61$, $p = 0.002$, df: 1863) for the mean grain angle: the mean angle was 2.6° and 3.1° for trees without and with cracks,

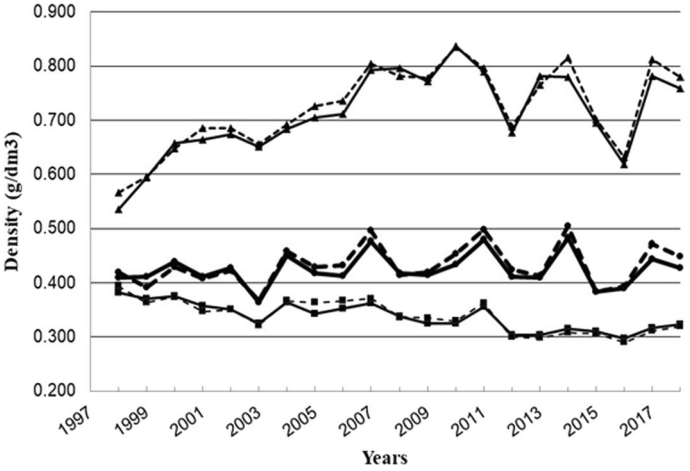


Fig. 5 Evolution over years of mean ring (Filled circle) density and of early- (Filled square) and of late-wood (Filled triangle) densities in trees with (dotted line) and without (solid line) cracking (the absence of *indicates that no significant difference between trees with and without cracks was detected)

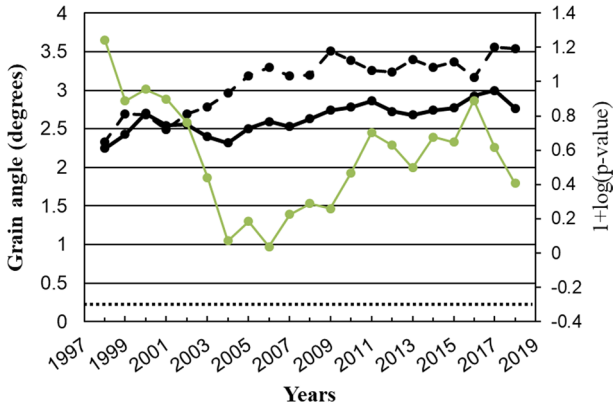


Fig. 6 Evolution of the mean spiral grain angle along annual rings in trees without (solid line) and with (dashed line) cracks. The green line corresponds to $1+\log(p$ values for tree type factor (with and without cracks)); the dotted line indicates the 5% significance level

respectively. Nevertheless, for any single annual ring, this difference was never significant (p value >0.10) but p values decreased sharply as early as in 2003 to reach their lowest values during the 2004–2006 period (Fig. 6 green line).

Discussion

Stem cracks are a major defect affecting several coniferous species and having detrimental consequences: weakening of trees, entry to pathogens and insects (Vasiliauskas et al. 2001), alteration of wood properties and a reduction in commercial timber value. The link with drought stress episodes is becoming better documented (Cameron 2019) and, with the increase in their frequency, observations of stem cracks are getting more and more

common. Nevertheless, the term 'crack' obviously encompasses different realities in the literature according to their position and size within the stem (internal ring cracks, longitudinal cracks) and their potential causes (release of internal tension due to drying, sunburn of bark and cambium). In this study, we focused only on longitudinal cracks, apparently the most common crack type in *Larix*.

Environmental and genetic effects on stem crack susceptibility

Cracking can indeed be a serious problem in larch as shown by this study, with more than half of the stems affected in *trial 1*. However even worse situations were encountered in France by Cazaux et al. (1993), who found hybrid larch plots of variety FP203 with over 60% and even 73% damaged stems. Clearly the severity is highly site-dependent, as shown in our study and by the latter authors: out of the 33 forest plots they evaluated (at the same age: 8 years), 30% were free of defect; 40% had less than 20% of stems damaged and 30% had more than 20% of stems with cracks. Although the authors suspected stem crack damage to be due to the summer drought of 1990, they could not link the damage variability they observed among sites to any specific environmental variables, either soil or climate.

Our study clearly identified the specific climatic conditions of 2003 (*trial 1*) and of 2018–2019 (*trial 2*) as the origin of the cracks, characterized by some of the driest summer months and highest summer temperatures (Fig. 1). The low frequency of damage in the irrigated plot in *trial 2* (Table 3) confirmed that extremely high temperatures by themselves are not enough to generate cracks as long as water is available, but in non-experimental conditions, high temperature and drought are often associated. Drought stress was reinforced on both sites by the low soil water holding capacity due to soil texture and made worse in *trial 1* by the site exposure (W) and slope.

However, in the lifetime of both plantations, some even drier years were recorded: either after 2003 (i.e. 2005 and 2016) in *trial 1* or before 2018–2019 (i.e. 2016) in *trial 2* without observation of any new cracks. This suggests that drought alone is not sufficient. Age of trees (and/or stem diameter) when a severe drought occurs appears to be another critical factor in connection to the occurrence of cracks. Authors studying spruces agree that stem cracks mostly occur in the juvenile phase, at ages ranging from 15 to 40 years (Persson 1994; Green et al. 2008; Kohler et al. 2018). For larch, this critical age seems much earlier: 6–8 years since planting. Cazaux et al. 1993 also observed cracks in hybrid larch 8 years after planting. Together with age, BH diameter also seems critical: Persson (1994) mentioned diameters of trees of at least 10 cm for Norway spruce, suggesting that thinner trees are not affected. In our study, this critical diameter was, on average, between 7 and 13 cm. This result confirms regular observations made in our genetic trials network that hybrid trees are mostly susceptible just before canopy closure and the first thinning at 10–15 years: at that time, height is around 10 m and BH diameter around 15 cm. At earlier stages (up to 5 years), we rarely observe cracks and after this critical period, new cracks are seldom noticed. Clearly, cracking occurs in the phase of juvenile wood formation, well-known for the weakness of several basic wood properties and particularly for its sensitivity to warping during drying (Zobel and Sprague 1998).

If an extreme drought environment can be regarded as a trigger for stem cracking, trees are obviously reacting differently according to species, families (and varieties) within species and finally among individuals. Some variability has been observed among larch species, with Japanese larch being, on average, more susceptible than European larch and their hybrid being at least as susceptible as Japanese larch (*trial 2*) (Table 5). Nevertheless, the

differences in damage frequency did not exceed 6%. A huge variability was found, in contrast, between families within species as shown in *trial 2* (Table 4). For the most seriously affected families, one stem out of three or even one out of two may suffer from cracking, but some families free of defects could be found in all three species. There can be even more stark contrasts, as detected for the commercial hybrid larch varieties in *trial 1*, with damage proportions ranging from 20 up to 70% (Table 1). It is worthwhile to note that the most affected varieties (Barres, FP201, FP203 and FP205) share a common narrow genetic variability as they correspond to full-sib families (or their equivalent). In comparison, the two others (Halle and FP211), which involve several parental clones of Japanese larch and/or European larch, offer broader genetic variability: this probably guarantees that they are exposed to a lower risk of damage.

Such a large genetic variability with respect to susceptibility to cracking has already been illustrated in the literature by Persson (1994) and Vasiliauskas et al. (2001) among provenances or clones of Norway spruce, although some other authors (Eriksson et al. 1975; Zeltins et al. 2018) found no genetic effect (at population and family levels) for the same species. In the same way, in the rare studies of genetic parameters of stem cracks, Zeltins et al. (2018) found a weak heritability (narrow-sense $h^2 = 0.09$/ family mean $h^2 = 0.2$) for the severity of longitudinal cracks in Norway spruce, whilst in contrast Hannrup et al. (2004) and Ball et al. (2001) showed a much stronger genetic control for internal cracks (or intra-ring checking): $h^2 = 0.45–0.57$ at clonal level and $h^2 = 0.64$ for Norway spruce and radiata pine respectively. This apparent discrepancy in results highlights the need to precisely characterize crack defects: longitudinal and internal cracks are clearly two different traits.

Can stem cracking be predicted based on external and internal tree characteristics?

Factors enhancing growth such as soil fertility (Kohler et al. 2018) or genetic effects (Persson 1994; Vasiliauskas et al. 2001) have been suggested as increasing the risk of crack damage. Even though at the species level, we could reach this conclusion—hybrid and Japanese larches with higher vigour were also slightly more prone to cracking compared to European larch (Table 3)—this link with growth was not seen in the variety trial (*trial 1*) (Table 1): the two most vigorous varieties were either the most or the least affected ones. In a well-designed genetic experiment with Norway spruce, Zeltins et al. (2018) also found no correlation ($r < 0.06$) at family level between diameter and cracking. Nevertheless, this latter study as well as our results (*trial 1*) highlight the unfavourable link between BH diameter and cracking within tested genetic units (respectively family and variety): trees with cracks consistently had a greater diameter than trees without cracks (Tables 1 and 5), a conclusion which converges on the general consensus that larger trees are more prone to cracking. This observation probably misled Cazaux et al. (1993) who qualified these cracks as 'growth cracks': studying only one hybrid variety (FP203), they had no visibility on how genetic variability for growth could affect susceptibility to cracks.

Remarkably nearly all studies mentioned in this paper agreed that the HD ratio of trees is critical with regards to crack susceptibility. Slender trees are less affected by cracking than thicker ones. This conclusion was also reached for larch, as shown by our results (Tables 1 and 5). Kohler et al. (2018) pointed out that a HD ratio of 70 or less was critical in Spruce and that its impact on the vulnerability to stem cracks was exponentially increased with site fertility. Similar HD ratios were found in our study for trees with cracks

(< 71). The wide spacing used in *trial 1* obviously favoured thicker and more tapered trees and, thus, a high proportion of damaged stems.

Besides external tree characteristics, thanks to wood sampling in *Trial 1*, we could retrospectively analyse internal wood traits over years and particularly around the time of crack appearance in 2003. By looking at pairs of trees with a similar diameter, we expected to detect which annual trait might weaken the wood structure and thereby explain cracking, excluding the tree size effect.

Significant differences between types of trees were found for ring width during the period 2000–2003, with the major difference observed in the dry year 2003 (Fig. 4). This concerned earlywood only, as latewood size (and proportion) did not significantly differ. Faster initial radial growth preceding cracking has often been proposed as enhancing cracking (Boulet-Gercourt and Nepveu 1988; Persson 1994 but not by Cameron et al. 2017).

Latewood size and proportion differences between cracked and uncracked trees have also been noted by several authors but without consistent results: less latewood has often been observed in trees with cracks (Day 1954; Dietrichson et al. 1985; Boulet-Gercourt and Nepveu 1988; Caspari and Sachsse 1990; Persson 1994) but this differs from our results, in which no differences were observed. In addition, latewood proportion was found to be either similar by Cameron et al. (2017) and by Zelnis et al. (2018) in spruces and in our study, but higher by Cameron et al. (2017) in grand and noble firs. Specifically, Cameron et al. (2017) used this difference of characteristics between spruce and firs to identify latewood as a potential source of vulnerability to cracking. They explained that proportionally wider (and denser) latewood in cracked trees compared to uncracked ones, in grand and noble firs compared to Sitka spruce, would induce tangential tension strain causing more cracking in firs than in spruces. Nevertheless, results by Boulet-Gercourt and Nepveu (1988), who found a lower latewood size and proportion in grand fir, obviously do not support this explanation.

The major contradiction with published results is for ring density. Indeed, while we observed no difference in wood ring density and each of its components (Fig. 5), there seems to be a general consensus in the literature that trees susceptible to cracks have an overall lower ring density than trees without cracks (Day 1954; Boulet-Gercourt and Nepveu 1988; Monchaux and Nepveu 1986; Persson 1994; Zelnis et al. 2018) even if these authors identified weakness not necessarily in the same tissue. For example, Grabner et al. (2006) and Rosner et al. (2018) found it in earlywood; Dietrichson et al. (1985) in latewood; Zelnis et al. (2018) in both and finally Boulet-Gercourt and Nepveu (1988) in transition wood. All of these authors worked on species with soft wood: either Norway spruce or firs; in larch, overall ring density—usually higher than that of spruces and firs, obviously does not play such a critical role in crack occurrence.

Finally, another trait which looks to be of some importance is the grain angle. Spiral grain is known to be a major defect in timber and end-products and its severity increases with grain angle (Säll 2002). It usually leads to severe deformation of wooden pieces during drying and it weakens their mechanical properties, particularly in the corewood, also characterized by high microfibril angles. During episodes of severe drought leading to internal loss of water in the wood, high spiral grain angle should create internal tensions in standing trees, leading to cracking, for the same reasons as twisting is observed in sawn timber when drying.

Grain angle is one of the major wood defects in *Larix* (Fujimoto et al. 2006). It is maximum in the juvenile wood where it is mostly of the S-helix type (left-handed type) before eventually changing to the Z-type (right-handed) (Ozawa 1972; Nakada 2004). The

left-handed spirality of the cracks observed for a large proportion of the trees in this study is thus coherent with grain angle trends.

Whilst grain angles at ring level were very similar between 1997 and 2001 (Fig. 6), they progressively diverged afterwards with greater angles in trees with cracks than in trees without cracks. However, these differences never became significant. A similar evolution was also recorded by Boulet-Gercourt and Nepveu (1988) in grand fir, with the grain angle of trees with cracks starting to diverge just one year or two before cracking occurred. Citing Dinwoodie (2000), Säll (2002) indicated that with an angle under 3°—the value we observed up to 2003 in our study—the impact on bending and compression strength of wood pieces could be negligible, but that above 3°—a value we observed from 2003 onwards—the strength (bending and tensile) in corewood could be reduced by more than 50%. It is thus reasonable to consider that the juvenile wood of trees with cracks with an angle superior to those of trees without cracks in 2002 and exceeding 3° thereafter has a lower mechanical strength leading, in conjunction with drought, to more frequent cracking. As spiral grain is reported to be under moderate to strong genetic control (Harris 1989), a reduction of grain angle through selection seems possible, as illustrated by Fujimoto et al. (2006) for Japanese larch.

However, if spiral grain can be detrimental to wood products, some authors (e.g. Kubler 1991) explain that spiral grain could also have a beneficial role in water and food supply to living trees because of more efficient distribution of resources to either branches or roots. Under stress, such trees might be at an advantage. As evidenced in our study (Tables 1 and 5), for a given variety or family, trees with cracks were, indeed, on average, more vigorous (greater BH diameters) than trees without cracks. The greater reduction in ring width observed following the appearance of cracks in 2003 (*trial 1*) would suggest a negative impact of cracking on further radial growth, but it should be noted first that this trend is only temporary: after a couple of years, radial growth was similar for the two types of trees. Secondly, this apparent paradox should not lead us to forget that trees with and without cracks were deliberately chosen for their similar diameter at the time of harvesting.

Conclusions

Like many conifers in temperate regions, larch is sensitive to stem cracking in the form of long longitudinal cracks. Summer drought has clearly been identified as the main trigger, and a critical period for their occurrence has been detected corresponding to the phase of juvenile wood formation. Even if cracks affect only the corewood and if healing of cracks can be rather rapid in larch, this defect is highly detrimental to timber quality and should be seriously considered with the increased frequency of drought events.

Based on our results, several practical recommendations can be made to foresters to alleviate the risk of crack formation in larch. First, a large variability among species, families within species and finally varieties has been observed with respect to their susceptibility to crack, so that a careful choice of appropriate planting material is recommended. Breeders will play a key role here, either directly by selecting crack-free genotypes (tested in drought susceptible sites for at least 10–15 years) or indirectly by genetically improving some traits like grain angle to reduce the risk of cracking. Varieties with a broader genetic basis would guarantee better behaviour with respect to cracking. Secondly, larch planting should be avoided on any drought-prone sites, particularly those with a low water holding capacity (< 75 mm following Cazaux et al. 1993), reinforced by southern/western

exposures and steep slopes. Thirdly, our study confirms a general conclusion found by many authors that a HD ratio lower than 70 greatly increases stem cracking risk. Therefore, any silvicultural treatments (e.g. wide spacing, heavy early thinning) in juvenile stands (during the first 15 years), causing trees to exhibit greater tapering should be avoided but in the limit of HD ratio compatible with stand stability to wind (optimally between 70 and 80 for juvenile stands according to Becquey and Riou-Nivert 1987).

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Authors' contributions LEP design of experimentation, data analysis, writing of the manuscript; DV field work (measurement and samples collection); FM sample preparation and wood properties analysis; DV and FM data curation.

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Availability of data and material The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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