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ORIGINAL ARTICLE

Summer drought and low earlywood density induce intra-annual radial cracks in conifers

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Abstract
Intra-annual radial cracks in conifers have a major impact on the quality of wood. However, the exact cause of their formation is still unclear. Some authors have proposed summer drought as the main cause of these cracks, whereas others have proposed winter desiccation. Wood from *Picea abies* trees grown at different sites in Europe (Italy, Switzerland and Sweden) was analysed. Radial cracks always occurred within one tree ring. Tree rings with lower earlywood density had a higher number of radial cracks. Combining the results from different sites, evidence was found that cracking occurred during severe summer droughts, characterized by high water deficits, probably because the hydrostatic tension within the tracheids exceeded the fracture limits of the middle lamella. According to these observations cracks may occur after a drought in any tree ring located in the sapwood that is characterized by a low earlywood density, with the exception of the outermost one. In conclusion, cracks cannot be used to date drought events at an annual resolution.

Keywords: *Dendroecology, earlywood density, radial cracks, summer drought, water stress.*

Introduction

Radial cracks in living trees occur usually as a consequence of internal stress induced by extreme environmental events. Frost and drought, together with wind and lightning, are the main climatic factors that may create internal stresses of such intensity that radial cracks in the wood of living trees result (Knuchel, 1947). Frost cracks are caused mainly by the shrinkage of wood owing to internal drying, which is produced by freezing out the cell-wall moisture into the lumens of wood cells (Mayer-Wegelin et al., 1962). The expansion of freezing water into living cell lumens, however, may also occasionally be responsible for cracking (Sano et al., 1989). Drought may also induce cracks because of severe wood shrinkage (Nördlinger, 1878; Barett, 1958; Aigner, 1981; Caspari & Sachsse, 1990; Persson, 1992; Pang et al., 1999; Grabner et al., 2001). Such cracks are usually large and affect the whole stem, reaching from pith to bark (Persson, 1992). Radial cracks in logs have a heavy impact on forestry and the timber industry, causing high economic losses (Caspari & Sachsse, 1990; Persson, 1992; Ball et al., 2001).

Tree growth is influenced by environmental factors. Past environmental conditions can be reconstructed by analysing tree rings. Tree-ring data (in particular width and density) have been widely used as a proxy to reconstruct past climate variations (e.g. Fritts, 1976; Hughes, 2002). Since tree rings are one of the few proxies with an annual resolution, they are highly relevant in climatology, reconstructing past trends and climate variability (IPCC, 2001). Tree rings provide information on past natural variability and on the baseline, i.e. information that may be used to evaluate whether current climatic conditions are within the range of natural variability, or whether they are altered by human impact.

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In general, climate change is expected to alter the frequency and intensity of extreme climatic events (IPCC, 2001). However, information on the past occurrence of such events is rare, and their frequency is difficult to assess. Anatomical features of wood can be used to assess the frequency of past extreme events. Some of these extreme events may leave diagnostic signals in the anatomical structure of wood. For example, late spring and summer drought periods induce intra-annual density fluctuations ("false rings") in tree rings (Wimmer et al., 2000; Rigling et al., 2002; Cherubini et al., 2003). Frost events were found to induce traumatic tissue formation because of cambium wounding (Glerum & Farrar, 1966; Stöckli, 1996; Knufinke, 1998). The most common signs found in the wood associated with frost and drought are, however, radial cracks. Radial cracks usually run over several rings and extend from the bark into the centre of the stems. Intra-annual radial cracks, reported for a number of coniferous species, are rarely seen (for a review see Cherubini et al., 1997). Although they were first described by Nördlinger (1878) over a century ago, and with considerable economic impact in today's plantation forests (Booker et al., 2000; Ball et al., 2001), they have been neglected in wood technology research for a long time. Polge (1984) observed that the wood surrounding intra-annual radial cracks has lower moisture. Caspari and Sachsse (1990) hypothesized that the high tension due to the water flow causes radial cracks. Booker (1994), Pang et al. (1999) and Booker et al. (2000) described cracking during drying of sawn timber with high moisture content and concluded that intra-annual radial cracks are caused by water tension and not by shrinkage during drying.

As intra-annual radial cracks are limited within one tree ring, they are supposed to allow past extreme events to be dated at an annual resolution. This makes them important in dendroecological and climatic research. The mechanism behind this type of cracking is still, however, only partially understood. For example, Cherubini et al. (1997) suggested that cracking is caused by winter desiccation, i.e. water imbalances in early spring, which result from frozen or very cold soils. The needles are suddenly warmed in sunny weather owing to sharp increases in air temperature, which induce high transpiration rates. Grabner et al. (2001), in contrast, claimed that summer drought is the driving force behind cracking.

The objective of this study was to clarify which climatic situations lead to the induction of radial cracks in living trees. Better understanding of the occurrence of cracks will help in finding forest management strategies to control the formation of radial cracks in future plantings. This study should also show the extent to which such cracks may be used as dendrochronological information sources in climatological studies.

Materials and methods

For this study, Norway spruce [*Picea abies* (L.) Karst.] samples already used by Cherubini et al. (1997) were reanalysed. The site was located at Paneveggio (Dolomites, Italy) with a mean annual precipitation of 1201 mm in the period 1922–1980. Another spruce site at La Sagne (Jura, Switzerland) had a mean annual precipitation of 1548 mm in the period 1901–1940. The spruce sites used by Grabner et al. (2001) at Hermanstorp and Knutstorp (clonal trials in southern Sweden), with mean annual precipitation of 636 and 679 mm, respectively, in the period 1978–1998 were also included. A detailed description of the sites is given in Table I.

The sample cross-sections were polished using sandpaper until individual tracheids became visible. Tree rings were measured to the nearest 0.01 mm using a LINTAB measuring device (Frank Rinn, Heidelberg, Germany). All ring-width series were cross-dated (Stokes & Smiley, 1968; Swetnam et al., 1985). Radial cracks were observed and counted both with the naked eye and under transmitted light microscopy (25 × magnification; Zeiss Stemi, 2000, Germany). X-ray density profiles were available for the Swedish spruce trees (Hermanstorp and Knutstorp) (Hannrup et al., 2004; Rozenberg et al., 2002).

The spruce samples from southern Sweden were used to illustrate the influence of wood density on the occurrence of cracks. The density profiles of 13 trees without cracks and 13 trees with a high number of cracks were averaged and plotted. According to the findings of Grabner et al. (2001), early summer precipitation (May, June and July) is most important in crack formation. The sum of early summer precipitation for the years in which most cracks occurred was therefore calculated for the sites at Hermanstorp (1978–1997), Paneveggio (1922–1941) and La Sagne (1905–1924). This was plotted against the number of cracks per tree ring.

At the Swedish sites a non-parametric correlation analysis (rank or Spearman correlation) was performed, taking into account the non-normality of the crack occurrence, between the number of cracks and the sum of May, June and July precipitation, lagged by 1 year (e.g. the number of cracks in 1991 correlated with the precipitation in 1992) using the period 1980–1997 ($n = 2275$). Such correlations were also calculated between the number of cracks and the tree-ring parameters earlywood density,

Table I. Details of the six studied sites.

Country	Site name	Location (lat., long.)	Elevation (m a.s.l.)	Species	Mean age (years)	No. of trees
Sweden	Hermanstorp	56°45′ N, 15°2′ E	180	*Picea abies*	19	182
Sweden	Knutstorp	55°58′ N, 13°18′ E	75	*Picea abies*	19	125
Italy	Paneveggio	46°18′ N, 11°38′ E	1800	*Picea abies*	200	135
Switzerland	La Sagne	47°02′ N, 6°47′ E	1200	*Picea abies*	130	7

minimum density, within-ring density standard deviation and ring density contrast. The latter is defined as the difference between the maximum latewood density and the minimum earlywood density within a single tree ring (Rozenberg et al., 2001).

Results

A typical diamond-shaped, intra-annual radial crack is shown in Figure 1A. The cracks usually extend from initial earlywood and continue into the latewood of the same tree ring. No traumatic tissue surrounding the cracks was found (Figure 1B), indicating that the cambium was not affected during crack formation. At the cellular structure level the cracks start in the middle lamella (Figure 1B). Most of the longitudinal tracheids surrounding the cracks were filled with resin, which indicates that living ray parenchyma cells were present at the time when the crack started. The cracks therefore formed in the sapwood, and not in the heartwood. At the Swedish fast growing plantation sites dented tree rings formed in 1992, i.e. the year of the summer drought, were observed (Figure 1A). These buckles were radially aligned with the cracks within the tree ring of 1991.

Analysing the data from the Swedish sites, the strongest relationship between the number of cracks and precipitation was found for the early summer period (May, June and July). Figure 2 illustrates the relationships between the total number of cracks and the sum of precipitation (May to July). At the Swedish site Hermanstorp, a negative relationship between the two parameters was found. The year 1992 had a very dry early summer, and a very high number of cracks was found in the preceding rings 1990 and 1991. The correlation analysis showed a significant relationship (Spearman correlation $r = -0.204$, $p < 0.001$) between the 1-year lagged sum of precipitation (MJJ) and the number of radial cracks. This pattern of a 1- or 2-year lag was found again at Paneveggio, where the droughts in 1925 and 1928 were preceded by peaks in the number of cracks in the tree rings from 1922, 1923, 1924 and 1927. At the La Sagne site, the dry early summer years 1911, 1913 and 1918 induced a high number of cracks in the rings from 1909, 1910, 1916 and 1917. Cracks do not occur after all drought years, as shown in Figure 2 (e.g. 1994 at Hermanstorp, 1936 at Paneveggio, and 1913 La Sagne).

The non-parametric correlation analysis (Spearman correlations) performed at the Swedish sites of tree ring 1991 showed that the highest correlation is between crack occurrence and earlywood density (Spearman correlation $r = -0.79$, $p < 0.001$) (Figure 3). Significant Spearman correlations were also found between crack occurrence and other ring

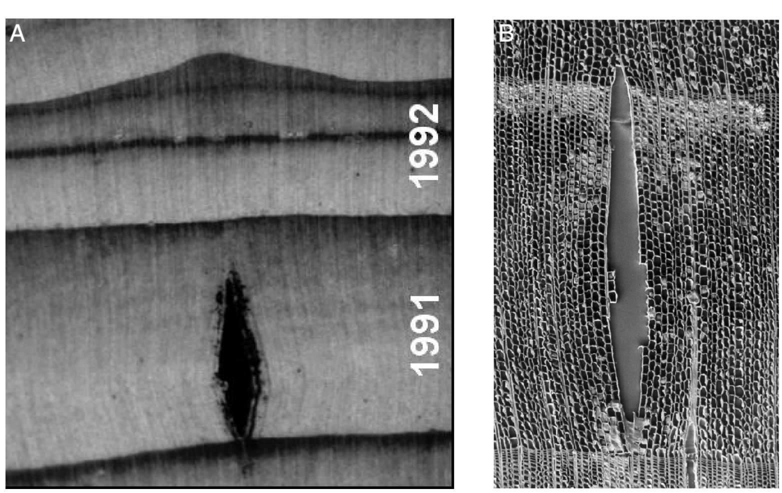

Figure 1. (A) Image of a radial crack (1991) and a dented ring border (1992), originating from a spruce tree grown in Hermanstorp (Sweden). (B) Scanning electron micrograph image of a radial crack from Paneveggio (Italy), showing the crack within the middle lamella.

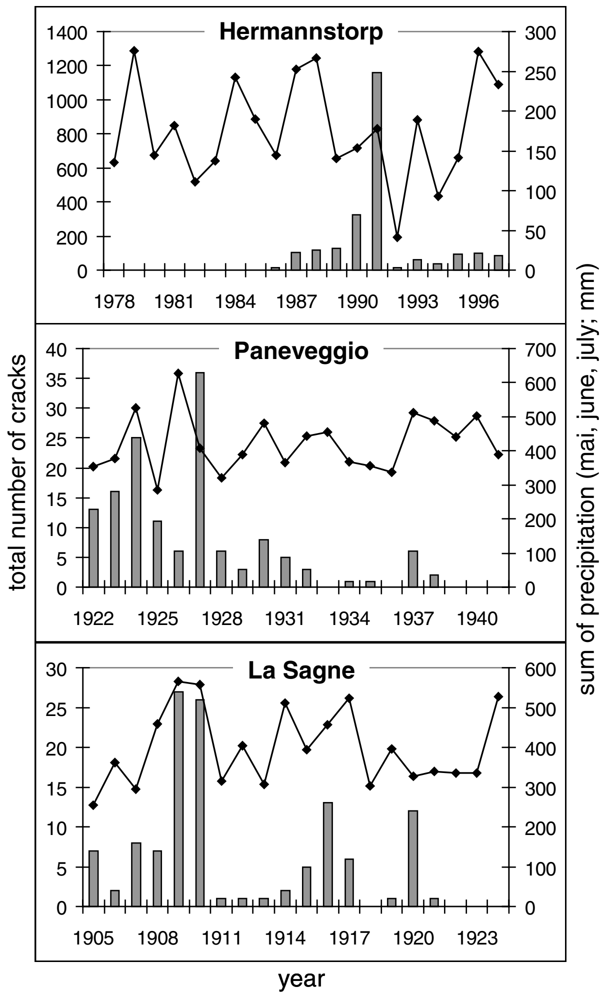

Figure 2. Relationship between the total number of cracks and the sum of precipitation (May to July) at Hermanstorp, Paneveggio and La Sagne. Bars = total number of cracks in all observed trees; lines = sum of precipitation from May to July.

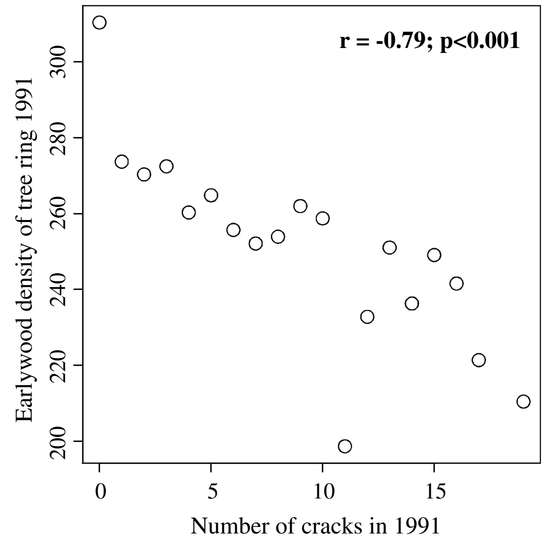

Figure 3. Relationship between number of cracks and earlywood density (ED) in tree rings in 1991; Norway spruce trees grown at Hermanstorp and Knutstorp in southern Sweden.

variables: minimum wood density ($r = -0.67$, $p < 0.01$), within-ring density standard deviation ($r = 0.74$, $p < 0.001$) and ring density contrast, i.e. the difference between the ring maximum and minimum densities ($r = 0.66$, $p < 0.01$). These three variables are related to earlywood density and thus logically significantly related to the occurrence of cracks. When studied among tree rings (i.e. among rings indexed by their year of formation), the strongest Spearman correlation coefficient was -0.78 ($p < 0.001$) and was found between earlywood density and crack occurrence. Among trees, the strongest relationships were weaker and were also found for earlywood density and minimum density with crack occurrence (Spearman $r = -0.46$, $p < 0.01$ for both ring variables). Among clones, the strongest relationships between crack occurrence and a ring variable were comparable to the correlations among trees and were again found for earlywood density and minimum density (Spearman $r = -0.47$ and -0.51, $p < 0.01$).

Such a general relationship observable at all levels (among rings, among trees and among clones) can be interpreted as a direct causal relationship: earlywood with low density has a lower mechanical resistance, facilitating the induction of cracks in the case of external stress.

To visualize the influence of the earlywood density on the occurrence of radial cracks, earlywood density profiles of 13 trees without cracks in 1991 were averaged and compared with 13 trees with the highest number of cracks in 1991 (between 13 and 19 cracks within the tree ring formed in 1991 in each tree) (Figure 4). The earlywood density of the tree ring formed in 1991 is the lowest in both curves. In all tree rings earlywood density was lower for the trees with a high number of radial cracks. The drought in 1994 at the Swedish sites did not lead to many radial cracks in the 1992 and 1993 tree rings, probably because of their high earlywood density (Figure 4).

Discussion

The intra-annual radial cracks are diamond shaped. In the radial direction they start in earlywood and end at the transition zone between the latewood and the earlywood of the following ring (Figure 1). Their maximum tangential extension is usually found in the earlywood. Neither traumatic tissue nor other cambium reactions (e.g. traumatic resin canals) occur close to the cracks. The cracks, as well as the adjacent tracheids, are filled with resin, as

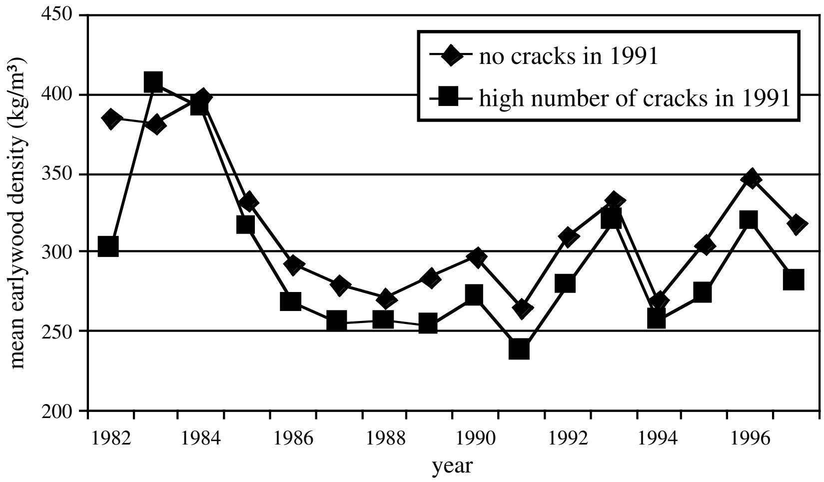

Figure 4. Mean X-ray density profiles of 13 trees with no cracks in 1991 and 13 trees with high numbers of cracks (13–19 per single tree) in 1991; Norway spruce trees grown at Hermanstorp and Knutstorp in southern Sweden.

observed previously (Nördlinger, 1878; Lutz, 1952; Cherubini et al., 1997; Grabner et al., 2001). These facts show that the cracking occurred when the wood tissue was already formed. The absence of any reaction of the cambium indicates that cracking either took place in the outermost ring when the cambium was dormant (Cherubini et al., 1997), or occurred during the growing season, but without affecting the cambium, most probably in the wood of some rings formed before the outermost ring. At a given time, when an extreme event occurs, all tree rings characterized by weak structure could crack synchronically. The existing resin in the cracks and the adjacent tracheids shows that cracking certainly occurs in the tree rings of the sapwood, as it is unlikely that cracks in the tree rings of the heartwood would be filled with resin.

Climatic events during the dormant season (winter desiccation, i.e. frost drought) have been proposed as possible causes of radial cracks by Lutz (1952) and Cherubini et al. (1997). However, radial cracks were observed in larch trees grown in Wales (UK) and Siberia without any further analyses. Since larch is a deciduous species, winter desiccation, as proposed by Lutz (1952) and Cherubini et al. (1997), can be excluded. Winter desiccation is caused by an abrupt starting of transpiration when, in early spring, air temperatures rise, but trees still have an insufficient water supply because the soil is cold or frozen (Kramer & Kozlowski, 1979; Tranquillini, 1979). At this time, there will be no green needle mass in larch trees. Therefore, it seems more likely that cracking occurs during the vegetation period, without affecting cambium activity.

Summer drought has already been suggested as a possible cause of intra-annual radial cracks (Reid & Mitchell, 1951; Caspari & Sachsse, 1990; Persson, 1992; Grabner et al., 2001). Grabner et al. (2001) claimed that cracks occur not in the outermost rings, but in tree rings formed 1 or 2 years before the year of the summer drought that triggers cracking (Figure 2). At the Swedish fast growing plantation sites (Hermanstorp and Knutstorp), Grabner et al. (2001) observed dented tree rings in 1991, i.e. the year before the summer drought of 1992. These buckles were radially aligned with the cracks in the tree ring of 1991 (Figure 1). Similar reactions of the cambium were also described by Nördlinger (1878). Since buckles were found in latewood (Grabner et al., 2001) and resin ducts occurred in high numbers (Cherubini et al., 1997; Grabner et al., 2001), it may be hypothesized that cracking takes place in previously formed tree rings, probably in summer when latewood formation starts (Persson, 1992). At the Swedish sites the severe summer drought in 1992 (also described in Vitas, 2001) induced radial cracks in the tree rings of 1990 and 1991, whereas the ring formed in 1992 contains the buckles and a high number of resin ducts.

The non-parametric correlation analysis showed a general relationship between the number of cracks and earlywood density, moderate at the tree and clone levels and quite high at the ring and general levels (Figure 3). The mean earlywood density of tree ring 1991 at the Swedish sites was generally low, probably owing to the particular climatic conditions in spring 1991 (Figure 4). Some previously published results based on the Swedish material showed that genetic control of crack occurrence in ring 1991 is strong (one of the strongest among all wood traits observed in this study; Hannrup et al., 2004), with a broad-sense heritability of 0.63 for the crack density in ring 1991 (Hannrup et al., 2004). The strong genetic control of crack occurrence in the ring formed in 1991 in the Norway spruce trees from the Swedish sites suggests that, at least for this species, it is possible to select genetically against crack occurrence to reduce the severity of the wood defects associated with cracks.

The mean earlywood density profile of the trees with the highest number of cracks is lower than that of rings without cracks (Figure 4). Significant correlations between crack occurrence and low earlywood density were found by Polge (1984), Caspari and Sachsse (1990) and Persson (1992). Radial cracks are usually found in juvenile rings (Nördlinger, 1878; Persson, 1992; Cherubini et al., 1997; Grabner et al., 2001). The earlywood density of the innermost rings is usually high. A decrease in the earlywood density usually occurs after the first innermost tree rings, before it increases with tree ageing (for a density profile of the first 16 tree rings, see Figure 4). A similar trend for the minimum density was described by Bräker (1981). According to the density profile, the most probable position of cracking would be in the late part of the juvenile wood, i.e. in rings between 6 and 15 years. Water reserves are higher in older than in younger trees (Larcher, 1984), which probably prevents cracking.

Polge (1984) described the surrounding tissue of the cracks as abnormally dry. Nördlinger (1878) and Persson (1992) mentioned that wood shrinkage could cause cracks, meaning that the moisture content has to be below fibre saturation. However, this hypothesis should be excluded because cracks were also found in wet trunks (Caspari and Sachsse, 1990) where shrinkage does not occur. Drought periods lead to an increasing water deficit, which leads to high tensions in the water column. The thin-walled earlywood tracheids contract with increasing water tension. If the tension in the earlywood becomes higher than the fracture limits of the middle lamella between adjacent tracheids, or between tracheids and ray parenchyma cells, an internal crack will be initiated. This phenomenon has been described by Booker (1994, 1996) and Pang et al. (1999) as taking place during technical drying of softwood.

It may be hypothesized that during extreme drought periods, which lead to high hydrostatic tension, the middle lamella may suddenly crack by exceeding the inherent fracture limits (Figure 1B). Because of the higher elasticity of non-fully lignified tracheids, the cracks rarely occur in the outermost tree ring, formed most recently. The cracks preferentially occur in tree rings with low earlywood density, 1 or 2 years after the formation of these rings. The low earlywood density in these rings is related to specific climatic conditions prevalent during the first part of the growing season and to the potential of wood density due to genetic factors. This time lag between the drought year and the occurrence of the cracks is clear in Figure 2. A severe summer drought, occurring 1 or 2 years after the formation of tree rings with low earlywood densities, has a high chance of causing radial cracks. Cracks do not occur after all drought years, as shown in Figure 2 (e.g. 1994 at Hermanstorp, 1936 at Paneveggio and 1913 La Sagne). The cracking leads to a reaction in the active cambium, which builds buckles along the radial alignments of the cracks at the border of the tree ring formed in the drought year (Figure 1). This cambial reaction becomes apparent in fast growing trees only, because in trees growing at a "normal' rate the number of tracheids formed through the cambial reaction is too low to detect.

In conclusion, the results show that tree rings characterized by very low earlywood density in sapwood, not the outermost ring, are prone to cracking. The formation of very low earlywood density, which is driven by climatic factors, has to coincide with a strong summer drought 1 or 2 years later, to cause cracks in the previously formed low-density ring. Earlywood density may be controlled through tree breeding and tree improvement programmes, to avoid radial cracks and their accompanying losses in wood quality. A higher risk of cracking can be expected in the future, as a result of current climatic changes, owing to the higher variability in climate and the higher likelihood of drought periods.

As cracks do not occur in the outermost tree ring, but one to three tree rings before, radial cracks cannot be used to date drought events at an annual resolution.

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