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ORIGINAL PAPER

Mortality of urban pines in Helsinki explored using tree rings and climate records

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Abstract The mortality of Scots pine trees in and around Helsinki has been reported in recent years, but the causalities of these deaths have not so far been rigorously examined. Tree-ring analyses have previously shown to effectively reveal historical growth variability and thus hint at the stress factors behind tree mortality. Here, we analyzed the tree rings of pines in two tree classes (living and dead) from an urban park in Helsinki to reveal their growth variations and to examine the obtained chronologies along with climatic data. Guided by tree-ring information, the pine growth over the past century could be divided into four episodes: average growth conditions during the first half of the twentieth century, a suppressed growth period during the 1950s and 1960s, a growth release since the mid-1970s, and a period of recent mortality. The two tree classes became particularly differentiated during the release period in that the growth of surviving pines underwent a more positive and abrupt growth anomaly in comparison to dead pines. The survival of pines could also be linked to their sensitivity to droughts in a long-term context: The growth of still-living pines showed a statistically significant moisture sensitivity over the second half of the century only. The period 2002–2003 (coinciding with drought) was observed as a dendrochronologically dated episode with a 40% mortality. Overall, the results point to the importance of tree competitive strength and climate as predisposing and inciting/contributing factors behind the tree mortality.

Keywords Climate change · Dendrochronology · Drought · *Pinus sylvestris* · Plant ecology · Urban ecology

Introduction

Adverse effects of recent droughts on the growth and vigor of pine and other tree species in Europe have been reported (Bigler et al. 2006; Dobbertin 2005; Martín-Benito et al. 2008; Martínez-Vilalta and Piñol 2002; van der Werf et al. 2007; Weber et al. 2007). Some of the evidence is related to a drought during the year 2003 that especially affected Central Europe (Fink et al. 2004) where the influence of the summer 2003 drought on vegetation was exacerbated by its length, the summer heat, and long sunshine duration (Rebetez et al. 2006). Consequently, the drought resulted in a 30% reduction in gross primary productivity across Europe (Ciais et al. 2005). A coinciding dry spell also occurred in Finland, where the drought lasted from August 2002 to October 2003, with the driest conditions in the southern part of the country. Deterioration of forest vitality was linked to drought damage with an estimated economic loss of 1–4 million Euros in forestry (Silander and Järvinen 2004). In addition to commercial forestry, the value of urban forestry and landscape trees is incalculable by virtue

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of their esthetic nature and psychological, medical, societal, physical, ecological, and chemical benefits (Dwyer et al. 1992). It is consequently worrisome that vegetation damage was also evident in the urban areas and that a large number of trees were reported dead or dying in Helsinki, especially in 2003. This mortality has likewise been associated with the coeval drought that prevailed in the region (Helama et al. 2009; Holopainen et al. 2006b; Silander and Järvinen 2004; Ympäristöraportoinnin asiantuntijatyöryhmä 2004). Specifically, a detailed study using digital aerial photography and field surveys had shown that the total amount of severely damaged forested areas represented about 25 ha in the city (Holopainen et al. 2006b).

Tree rings provide measures of tree growth, and chronologies of tree rings are commonly examined to investigate ecological and climatic influences on the radial growth of trees (Fritts 1976; Fritts and Swetnam 1989). The external or internal signals of growth and disturbance can be extracted from the overall growth variability using dendrochronological analyses of tree-ring series. Typically, these factors can originate from stand dynamics or ontogenetic or climatic origins (Cook 1987). Moreover, tree rings can be directly calibrated against the records of weather stations (Fritts 1962; Fritts et al. 1971). Such analyses can quantitatively diagnose the climate–growth relationships in a given population and thus help in evaluating the relative importance of meteorological variables to tree vigor. Topically, recent research has demonstrated how tree-ring data and their analyses can reveal the ways that the dendroclimatic responses of trees are changing as a function of time (Biondi 1997), how the response may alter due to tree aging (Carrer and Urbinati 2004) or social status as indicated by crown class (Martín-Benito et al. 2008), or how the climate–growth relationships change as the tree size increases (De Luis et al. 2009). Moreover, dendrochronology can be used to determine the post-mortem ages (time since death) of each tree and thus examine the mortality patterns (Cherubini et al. 2002; Lombardi et al. 2008; Rouvinen et al. 2002; Villalba and Veblen 1998). All of these uses of tree-ring analyses make them ideal tools for revealing the patterns and causalities of mortality episodes. In fact, the tree rings can be used as indicators of tree growth vigor and the hierarchy of environmental stress, to an extent even predicting tree death using dendrochronological data (Bigler and Bugmann 2004; Ogle et al. 2000; Pedersen 1998).

Here, we aim toward a deeper understanding of the potential causes and controls of the recent Scots pine (*Pinus sylvestris* L.) mortality that has been reported in southern Finland, with sites in and around Helsinki (Holopainen et al. 2006b). Tree rings of surviving and dead pines were examined in the context of dendroclimatology and dendroecology (Fritts 1976; Fritts and Swetnam 1989). The goal of the study was to ascertain and further detail the role of climatic or other types of disturbances on the mortality of the trees. Mortality has previously been suggested to be occurring in association with rocky slopes of the landscape (Holopainen et al. 2006b; Ympäristöraportoinnin asiantuntijatyöryhmä 2004), and the pines in this study were sampled from similar environments. In brief, our target was to retrospectively quantify the observed mortality of pines using tree-ring analyses and pre-mortem growth patterns and their relationships to climatic variations. Thus, we aimed to see if these data could explain why some trees appear healthy while others died.

Materials and methods

Dendrochronological techniques

Annala Manor House, Villa Anneberg, dates to the 1820s (Donner 2005; Ranta et al. 2005). It is located in Vanhakaupunki in Helsinki, at Hämeentie 154, and owned by the City of Helsinki. The manor house park is in a smoothly contoured landscape with rocky slopes, between ~15 and 25 m above the sea level. An organic soil layer of about 40 cm covers the Precambrian bedrock (Helama et al. 2009). Ten living pines (with green needles) and ten dead pines (lack of green needles) were chosen randomly and sampled in the park with an increment borer. The cause of death for the dead pines was not observable; there were no biotic (e.g., fungal disease) or abiotic signs associated with mortality. The borer was used to extract cores at breast height on each tree's north side for tree-ring analysis. Circumference (including bark) of the stem was measured at the same height.

The ring widths were measured from each core to the nearest hundredth of a millimetre. The ring width index series were cross-dated using the dendrochronological approach of Aniol (1983) and Holmes (1983) along with visual comparison of the produced time series. Dendrochronological cross-dating of series by their ring width characteristics (narrow and wide rings) produces absolute dating of each sample to an accuracy of one calendar year (Fritts 1976). Sampling was performed in 13 July 2007, so that the historically youngest ring of living pines, which was found partially formed, was preliminarily dated to that same year. In the case of dead pines, the tree-ring series were cross-dated against each other and against the chronology that comprised the living pines. Temporal synchronization with unambiguous cross-matches was taken as an accepted date for each series. The post-mortem age of the dead pines could thus be estimated as the difference between the year of sampling and the year of the last identifiable ring.

Cambial trends

Tree-ring width series are known to contain non-climatic variability that should be removed prior to dendroclimatic interpretations. First, the tree rings tend to grow wider when trees are young, with a diminishment in width as a function of tree age. The theoretical age trend was estimated here by aligning the rings by their cambial ages (in practice, ring number counting from pith), instead of calendar years, and calculating a mean value of ring width for each ring number. The averaging was made using a biweight robust mean (Cook 1985; Mosteller and Tukey 1977). Subsequently, a negative exponential curve was fitted to the measurement series, and indices were derived from the curve by division. Using the formula of Fritts et al. (1969), a negative exponential curve can be expressed as:

$$t_a = je^{-ca} + m \tag{1}$$

where t_a is the value of the trend in ontogenetic year a (in practice, ring number), j approximates the level of juvenile growth, c controls the trend concavity, and m is the mature growth level in an old tree (Fritts et al. 1969). The curve modeled in this way can be designated the RCS curve (regional curve standardization; Briffa and Melvin 2011); that is, the measured tree-ring values were divided by the value of the curve Eq. 1 specific to tree class (living vs. dead) to derive the index (i) series. Subsequently, the indices were aligned according to their cross-dated calendar years and averaged into chronology using biweight robust estimation.

Relative growth rate could be assessed “according to the ratio of the radius of each tree divided by the radius of the single, overall-sample RCS curve at the point corresponding to the final age of that tree” (Briffa and Melvin 2011). Here, we simply define this relative growth rate (RGR) mathematically as:

$$\mathrm{RGR} = \sum_{a=1}^{n} w_a \Big/ \sum_{a=1}^{n} \bar{w}_a \tag{2}$$

where w_a is the width of a tree-ring in year a in the series possessing n tree rings and $\bar{w}_a$ is the mean width of all rings in year a. This measure was determined separately for each tree.

Double de-trending

Second, the tree-ring series may contain growth pulses caused by ecological disturbances (Cook 1985, 1987). Consequently, it is common practice to index the ring width series by a spline function (Cook and Peters 1981) with a frequency response of two-thirds of the individual series length with a 50% cutoff (Cook 1985). The spline was fitted to the ratio-based indices from the first detrending, and final indices were derived from the curve by division. Eventually, the first detrending approach (RCS) was expected to remove the trend attributable to biological aging of the trees (Briffa and Melvin 2011), whereas this fairly stiff spline function exploited in the second approach of detrending was expected to capture tree-ring variation related to disturbances caused by forest dynamics (Cook 1985). The series of tree-ring widths thus was indexed using the two-step process of Holmes et al. (1986) called double-detrending.

Following the previously applied protocol (Helama et al. 2009), the series of individual pines was characterized for their first-order autocorrelation and the amplitude of their growth variations, calculated using standard deviation and mean sensitivity (MS). The latter was determined by Fritts (1976) as:

$$\mathrm{MS} = \frac{1}{n-1}\sum_{a=1}^{n-1}\left|\frac{2(i_{a+1} - i_a)}{i_{a+1} + i_a}\right| \tag{3}$$

where i is the tree-ring index of year a in the series possessing n tree rings. When compared with standard deviation, mean sensitivity is a measure of the variation between consecutive years (i.e., variability at inter-annual time scales).

The indices were further pre-whitened using the Box and Jenkins (1970) methods of autoregressive and moving-average time series modeling (Cook 1985; Henttonen 1984; Monserud 1986). The order of the autoregressive moving-average process was determined using Akaike (1974) information criteria. Prewhitening transforms autocorrelated series into a series of independent observations by extracting residuals from the modeled process. Chronologies were produced averaging the annual values of indices by a biweight robust mean (Cook 1985; Mosteller and Tukey 1977). To do so, the last and partially formed ring in each series was omitted prior to averaging.

Dendroclimatological analyses

Tree-ring width variability was compared with monthly meteorological observations from the weather station of Helsinki that has provided climate records for mean temperatures and precipitation sums since 1829 and 1845, respectively. Monthly records were homogenized, taking into consideration the changes in devices and observation sites (Tuomenvirta 2004). Identification of climatic features that significantly affected tree-ring growth was achieved using bootstrapped correlation analysis and response functions in a form of principal component regression that was designed to account for the commonly occurring multi-collinearity of the monthly climatic variables (Fritts 1976). Each bootstrap estimate was obtained by generating 1,000 samples (Biondi 1997; Biondi and Waikul 2004). These analyses made use of double-detrended and prewhitened tree-ring indices and linearly detrended climate records. Response analyses were done separately for the two types of tree-ring chronologies, those comprising living and dead pines.

Results

Cross-dating and postmortem ages

Two tree ring chronologies were constructed. The chronology of still-living pines spanned between the years 1850 and 2007, whereas the chronology of the dead pines started from the year 1831 with the last ring in 2006 (Fig. 1a). Visual and statistical comparison of the two chronologies showed a positive association with markedly high statistical correlation as determined for double-detrended and prewhitened data (Fig. 1b). The postmortem ages of the dead pines varied between 1 and 45 years (Fig. 1c). Four out of ten pines had their last ring date either at 2002 or 2003.

Growth characteristics

The mean circumferences (including bark) were not statistically different between living and dead pines, and neither were the lengths (i.e., number of rings) of the series (Table 1). Relative growth rates Eq. 2 of the series were alike; their means, grouped by the two tree classes (living vs. dead), did not show a statistically significant difference. Consistently, the trends of aging were highly similar and almost indistinguishable between the two tree classes (Fig. 2). Similarly, the differences in mean sensitivities, standard deviations, and autocorrelations were not statistically significant between the two tree classes (Table 1). The results were alike whether the mean sensitivities, standard deviations, and autocorrelations were calculated before or after the prewhitening (not shown).

Chronologies and growth periods

We next used the RCS chronologies of living and dead pines to portray the overall growth variations. Of interest, the two chronologies showed intervals of time during which their growth appeared rather similar, but also a period of growth alteration (Fig. 3). More specifically, the pine growth could be divided into four episodes as evidenced by tree rings: the average growth conditions until the 1940s (I), the suppressed growth period during the 1950s and 1960s (II), the subsequent growth release since the mid-1970s (III), and the period of recent mortality (IV).

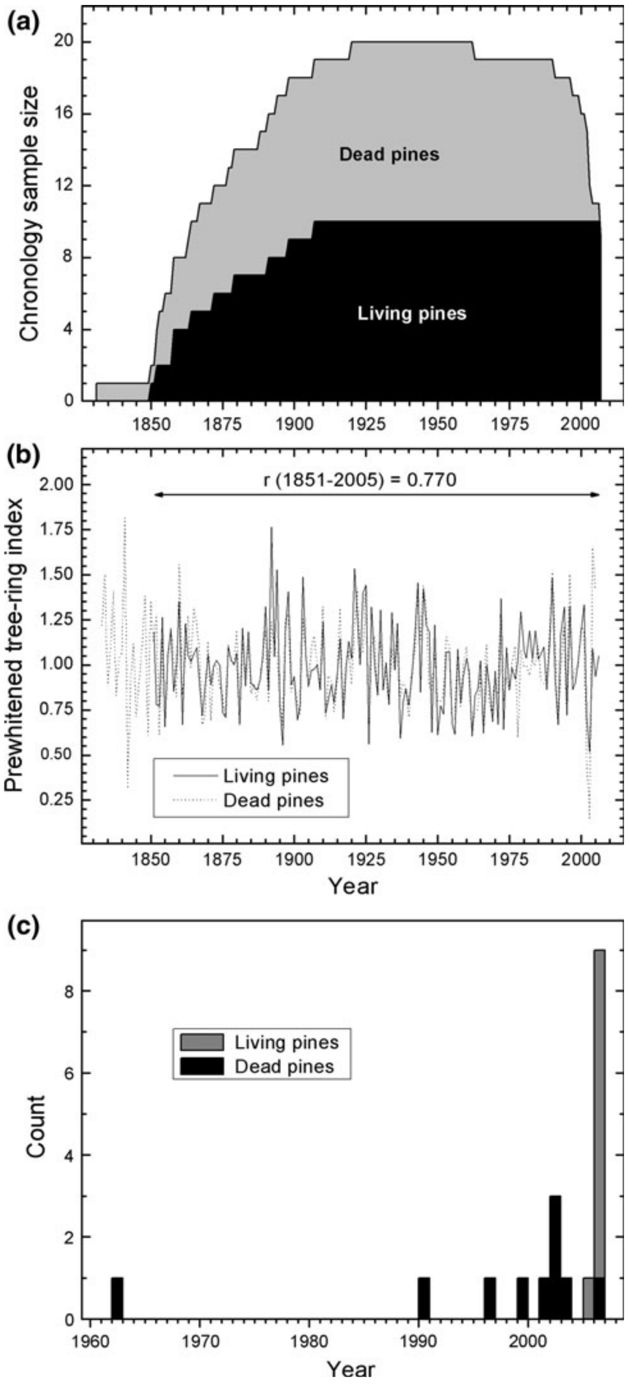

Fig. 1 Temporal evolution in the chronology sample series (a number of cross-dated tree-ring series per year) of living and dead pines (**a**). Visual and statistical comparison of the living and the dead pine tree-ring index series reveals positive and high correlation (**b**). Yearly distribution of the last observable growth of living and dead pines, as achieved by dendrochronological cross dating, indicating in the case of the dead pines the postmortem ages of the trees (**c**)

Period I was characterized by tree-ring variations around the expected index value of 1.0. Occasionally, the indices

Table 1 Characterization of the pines by their circumferences at breast height (CBH), the series of tree-ring widths by their lengths (*L*) and relative growth rates (RGR; Eq. 2), and the series of tree-ring indices by the standard deviations (SD), mean sensitivities (MS; Eq. 3), and first-order autocorrelations (AR), calculated subsequent to the first detrending approach

	CBH	*L*	RGR	SD	MS	AR
Living	130.7	135.0	1.015	0.656	0.320	0.761
Dead	130.9	127.3	0.980	0.571	0.296	0.763
p	0.988	0.495	0.603	0.171	0.257	0.954

Differences between means were compared using *t* tests (unpaired samples with unequal variance) with accompanying statistical significances (*p*)

of living pines showed higher values in comparison to indices of dead pines (e.g., during the 1890s), but there were periods during which the indices of dead pines indicated increased growth in relation to the growth of living pines (e.g., during the 1920s). Subsequently, period II manifested itself as a clear suppression of growth. The tree-ring index values remained persistently below the value of 1.0 between the years 1948 and 1978 in both chronologies. The following period III started with high index values in the chronology of still-living pines, whereas the tree-ring indices of the now-dead pines remained pervasively below the value of 1.0 until the year 1989. This pattern indicated an approximate decade-long lag in the growth release in relation to still-living pines among the now-dead pines.

Period IV was characterized by slightly lower tree-ring index values of dead pines in comparison to the indices of the living pine chronology, with evidence for the mortality between 1990 and 2006. Of note, the chronology of dead pines showed lower index values than the chronology of living pines constantly since the year 1973. The year 2003 appeared as the most negative growth anomaly for all studied pines since the suppression.

Dendroclimatic responses

Response functions were produced using the information about the growth periods, calculated over the first and second halves of the 20th century. These were the intervals of time with similar and altered growth, as judged by the temporal characterization of the RCS chronologies. During the earlier half of the century (1901–1950), the only statistically significant variable found influencing pine growth was precipitation in June (Fig. 4). This relationship was not strong but was positive. In contrast, the analysis of the living pine chronology revealed no statistically significant associations between climate and tree radial growth.

The results of the dendroclimatic responses over the later half of the century (1951–2000) were dissimilar. The pines in both classes (living vs. dead) appeared to benefit from late-summer warmth and mid-summer rainfall, as evidenced by the positive and statistically significant associations between the tree-ring chronologies and August temperature and total July precipitation, respectively (Fig. 4). The still-living pines appeared also to benefit from the warmth of the spring season, as demonstrated by the positive and statistically significant relationship between the tree rings and April temperatures, whereas the now-dead pines exhibited considerably lower correlation with the same climatic parameter.

Climatic variations

Tree-ring chronologies were compared with the climatic fluctuations as recorded in the meteorological station. The meteorological records of Helsinki showed that the warm-season temperatures have been warming over the past decades. This rise was evident both in April and August temperatures (Fig. 5). Several dry July months during the 1990s were evident, as were exceptionally dry post-2000 years, manifested especially as a paucity of July rainfall.

Discussion

Despite the similarities of dendrochronological information between the historical tree-ring variations of healthy and dead trees (Table 1; Fig. 1b), there were noticeable historical growth differences between the living and now-dead pines observed in their long-term growth changes: The two tree-ring chronologies appeared to show differentiated growth levels subsequent to the growth suppression of the 1950s and 1960s. First, the period of suppression did not overlap with strong climatic deteriorations (see Fig. 5), and we associate the lowered growth levels during this period with a suppressive effect of over-density on the radial increment. Thereafter, the currently living pines exhibited a stronger growth release starting in the mid-1970s (Fig. 3). In this context, a growth release resulting from horticultural activities could be expected as the radial growth of Scots pine is known to react positively and with similar amplitude to stand thinning from north (Helama et al. 2008) to south (Río et al. 2008) of its biogeographical distribution. We have found no written documentation of historical

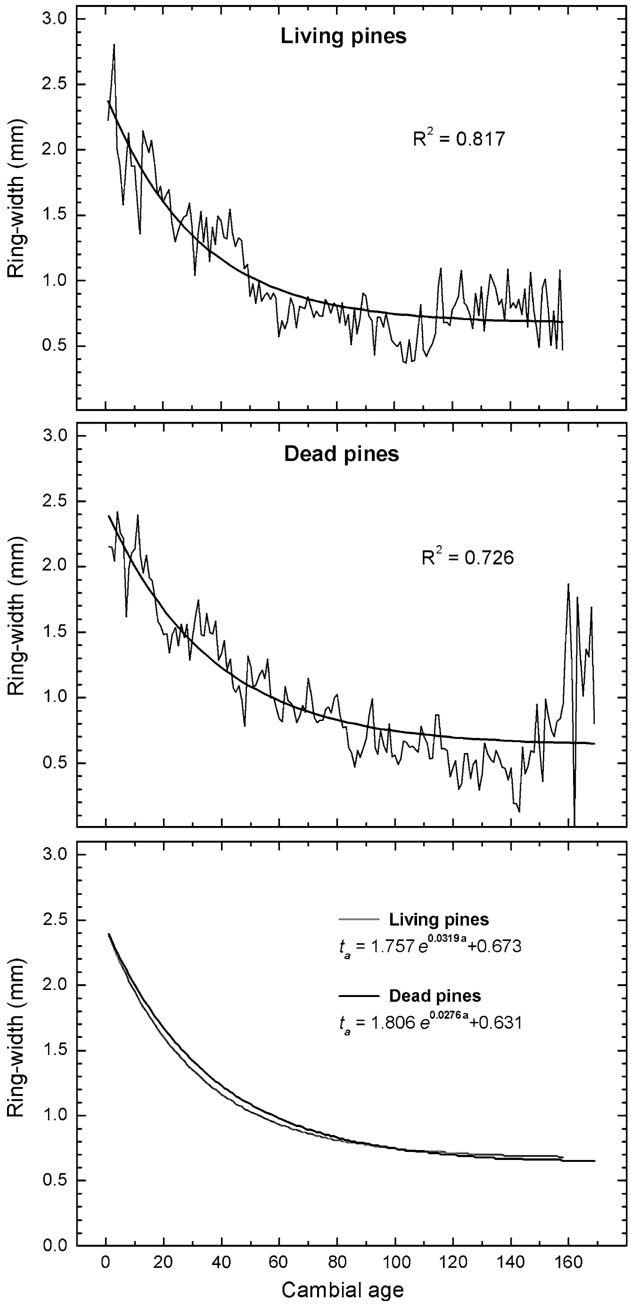

Fig. 2 Determination and comparison of observed and modeled (Eq. 1) mean growth curves using dendrochronological data for living and dead pines. The coefficient of determination (R^2) shows the observed (*thinner line*) variance explained by the models (*thicker line*)

horticultural activities in the park, but it is known (Matti Selänniemi, personal communication) that thinning of competing birches was carried out in the park at least during the early years of the 1980s. This information did not contradict the tree-ring evidence and could actually suggest the possibility of earlier thinnings as a conceivable part of the horticultural history. The differentiated historical growth of still-living and now-dead pines during the release could, from an ecological point of view, indicate relatively recent changes in their positions of relative competitive strength. It could be further postulated that the relative newness of this change could explain the non-significant differences in the circumferences and relative growth rates (Table 1) between the two tree classes.

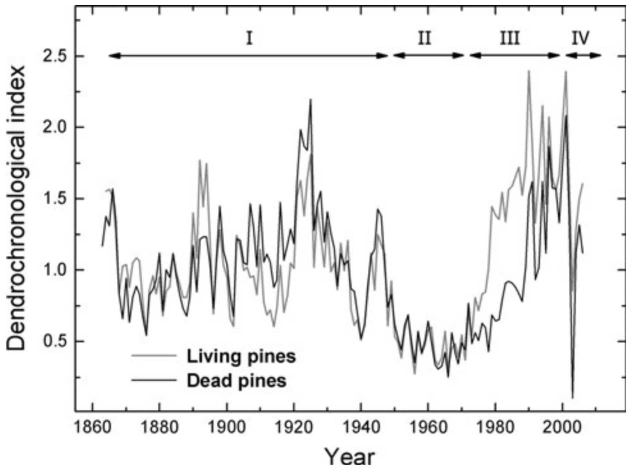

Fig. 3 Growth variations of living and dead pines as tree-ring chronologies subsequent to the first detrending. Four periods (*I*, *II*, *III*, and *IV*) of growth were determined. The chronologies of living and dead trees are shown since 1864 and 1863 when the chronologies were covered using at least five pines (Läänelaid 2000)

Variation in summer moisture was the most pervasive factor influencing growth. This dendroclimatic response was a positive correlation between tree rings and precipitation in June/July (Fig. 4). The finding indicates that the rainfall deficit during the Scots pine growing season would result in lowered radial growth in the studied population. The now-dead pines had been sensitive to summer droughts significantly longer than the currently living pines, over the full period of climate analysis. Several recent studies have identified similarly adverse effects of droughts on Scots pine growth and survival (Bigler et al. 2006; Helama and Lindholm 2003; Hordo et al. 2011; Mandre et al. 2010; Oberhuber 2001; Oberhuber and Kofler 2000; Oberhuber et al. 1998; Pichler and Oberhuber 2007; Weber et al. 2007). Yet, a tree-ring network showed the effect of the total precipitation during May through July in every studied site in southern Finland (Henttonen 1984). According to Eilmann et al. (2006), not only the ring width, but also the cell number was reduced in Scots pine stems during drought years in an Alpine dry valley in Switzerland. Ozolinčius et al. (2009) demonstrated a decrease in needle age and crown defoliation of Scots pine as a result of drought. Moreover, Pouttu and Dobbertin (2000), using the needle trace method, correlated a decrease in foliage of Scots pine with severe droughts over much of the twentieth century. In the same context, *Pinus* trees have also been shown to be more prone to drought-induced xylem embolism than other

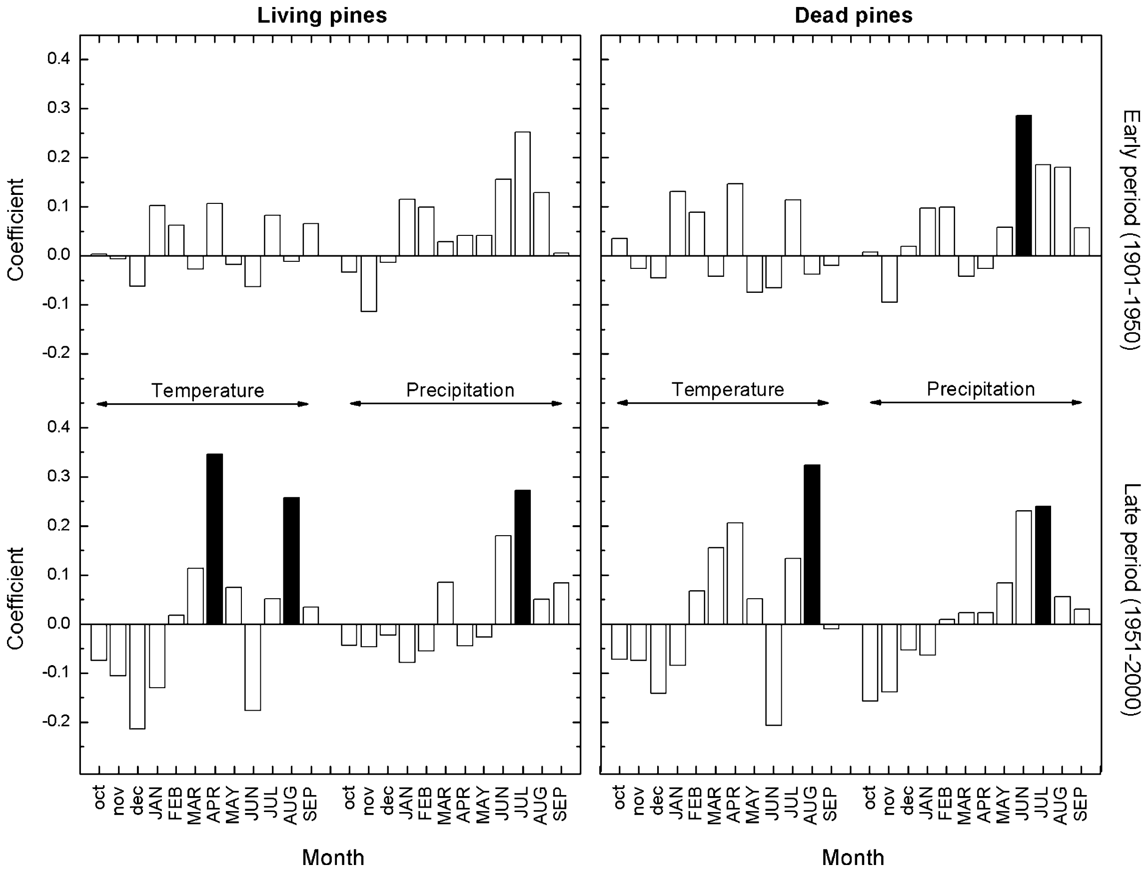

Fig. 4 Bootstrapped response functions show the relationships between the tree rings and monthly meteorological variables of previous (*small letters*) and concurrent year (*capital letters*) to growth over the early and late periods. Calculations were performed separately for living and dead pines. Statistically significant relationships (0.05 level) are indicated as filled histograms

conifers (Martínez-Vilalta and Piñol 2002; Martínez-Vilalta et al. 2004).

Natural tree death is an ecological process that is commonly a consequence of several overlapping agents of mortality (Franklin et al. 1987; Peet and Christensen 1987; Manion 1991). Intertwining our findings of moisture sensitivity in relation to the relative competitive strength of the trees, the results of this analysis agreed markedly with an earlier suggestion (Bigler et al. 2006) that both competition and previous droughts may impair Scots pines in a long-term context, making them vulnerable to subsequent contributing factors, such as recurring drought. This line of reasoning was further supported by our observation (see above) that the now-dead pines had been sensitive to summer droughts much longer than the currently living pines, over the whole of the twentieth century (Fig. 4). This compound interpretation of competition and droughts also agrees well with the finding that annual increments of suppressed Scots pines undergo more distinct drought-related growth reductions than the dominant pines (Pichler and Oberhuber 2007). In addition, the suppressed pines have been shown to recover slowly after drought events (Martín-Benito et al. 2008). Eventually, this pattern would be in agreement with Bigler et al. (2006), who presumed that the long-term influence of competition could predispose Scots pine trees to die, while the droughts could additionally act as temporally overlapping inciting mortality factors.

Another difference in the historic response of the living and dead trees to climatic variations also emerged: only the currently living pines were statistically significantly linked with mean temperatures in April. A similar response was detected previously for Scots pine in southern Finland (Holopainen et al. 2006a; Laitakari 1920) and in Estonia (Hordo et al. 2009; Läänelaid and Eckstein 2003). According to Hordo et al. (2011), the tree rings of the same species and particularly the temperature of mid-March to early April correlate positively and statistically significantly in several regions from Estonia to Finnish Lapland. In Helsinki, the tree mortality has in general been suggested to occur in association with the rocky slopes of the landscape (Holopainen et al. 2006b; Ympäristöraportoinnin asiantuntijatyöryhmä 2004). These are the microenvironments that may be considerably wind-exposed and thereby

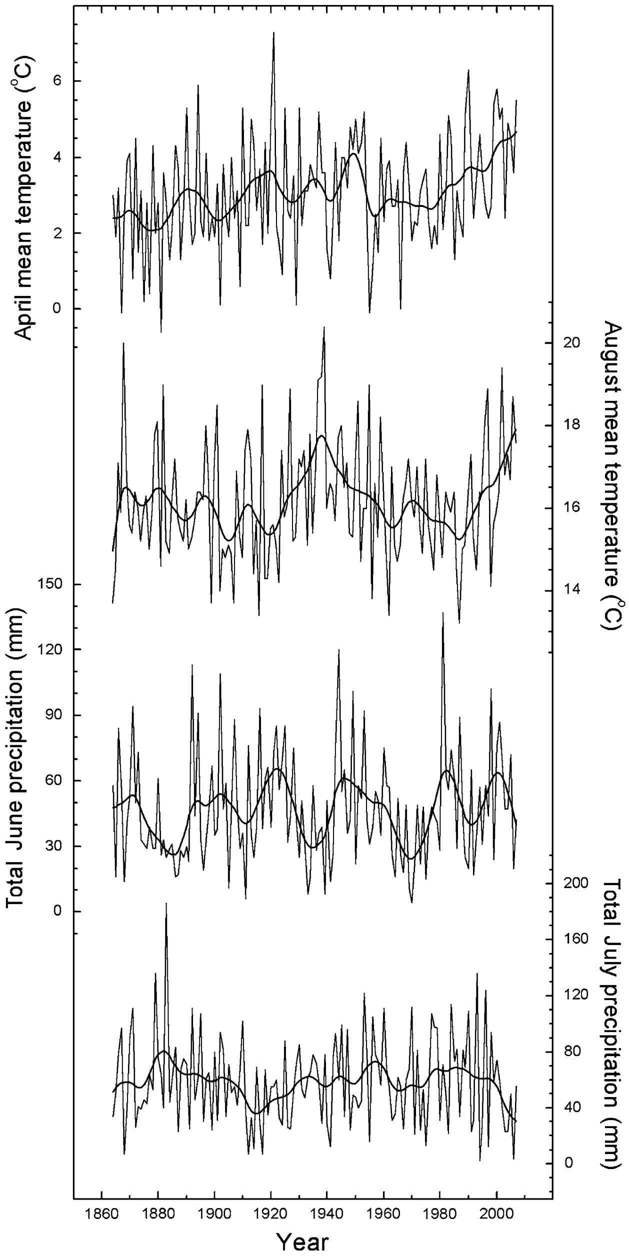

Fig. 5 Climate fluctuations over the period of tree-ring chronologies exemplified with the particular monthly mean temperatures and precipitation sums influencing the pine growth (see Fig. 4). *Thin* and *thick lines* represent the yearly and decade-scale variations

possess a relatively thin snow cover during the winter. Accordingly, the positive response of living trees to April temperatures could be hypothetically associated with the potential of warm (cool) Aprils resulting in rapid (delayed) snow-melt during the spring. This assumption appears especially reasonable because April is a key month in the process of snow-melt in Helsinki (Helama et al. 2009), and a lack of similar response could be expected in the sites with only a thin snow cover. In addition, delayed snow-melt has previously been connected with reduced tree-ring growth in northern conifers (Vaganov et al. 1999). Furthermore, the data indicated that April temperatures exhibited trends of warming roughly over the past three decades (Fig. 5), trends that peculiarly overlapped with the growth release evident especially in the chronology of living pines (Fig. 3). Conceivably, judging by their contrasting dendroclimatic responses to April temperatures (Fig. 4), the currently living pines may have benefitted from this warming with concomitant growth addition relative to now-dead pines over the recent decades. This inference would agree with the proposition that the rate of post-thinning growth amelioration may be explained by the advantageousness of the prevailing climate conditions (Helama et al. 2008).

Of interest, the last observable growth years of the now-dead pines represented a time interval of several years between 1962 and 2006. While the oldest post-mortem age of a snag (i.e., the pine with its last ring in 1962) clearly represented a preceding death event with no probable connection to the recently quantified mortality of urban trees (Holopainen et al. 2006b), it is notable that four out of ten pines had indeed grown their last ring either in 2002 or 2003. However, the growth of four pines had ceased prior to the 2002–2003 event with their last rings dated to the years between 1990 and 2001. Although any generalization of this outcome would appear somewhat restricted by the sample size (ultimately limited by the fieldwork permission from the City of Helsinki), the results indicate that not all trees found dead in the surveys subsequent to the climatic extreme (2002–2003) had actually died as a consequence of that event. We therefore note that this factor could imply a risk of overestimation with regards to the 2002–2003 mortality and its overall severity.

Worth emphasizing is that the July months especially have been markedly dry in a number of years over the 1990s in the study region (Helama et al. 2009). These summers were the years 1991, 1994, 1995, and 1997 (Fig. 5). The continuation of the dry summers in the course of the 1990s could have contributed to and incited pine mortality in the region prior to and during the 2002–2003 climate event, respectively. This finding is parallel to observations of Pouttu and Dobbertin (2000), who demonstrated an association between the periods of dry years (rather than single-year events) and the most severe decreases in foliage of Scots pine. Conceivably, multi-year periods of drought initiated prolonged growth declines in Scots pine and may have much more adverse and decisive effects on growth and survival than solitary events (Bigler et al. 2006).

Finally, two pines showed their last ring in 2006 (Fig. 1c). Of note, the summer of this year was exceptionally dry (Venäläinen et al. 2009), as can be seen by the record-low precipitation in July (Fig. 5). The dead pine with its last ring in 2006 was observed with red needles during the fieldwork (and with no needles in the next summer, 2008) while the other pine with its last ring dated to 2006 was judged to still be living during the fieldwork (Fig. 1c). The cessation of radial growth is known to occur first along the non-branchy part of the Scots pine stem, second in the basal part, and finally at the top (Leikola 1969). In addition, a discrepancy between the last-formed ring and last green needles in the crown has been observed for other species (Cherubini et al. 2002). For Scots pine, a lapse of even several decades could be expected when the pines are dying because of senescence (Leikola 1969). The evidently much shorter delay in the case of the studied pines could indicate the power of the given climatic disturbances versus death due to senescence. The differentiated growth cessation in different vertical positions of the stem naturally complicates any detailed estimation of the post-mortem age of the pines. The issue would also explain why one pine was judged living in 2007 with no observable growth at breast height. As an additional consequence, it cannot be ruled out that the pines showing their last ring in any particular calendar year (Fig. 1c) still did not yield a growth layer in a lower or higher position in the next year.

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