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Temporal mortality pattern of pedunculate oaks in southern Sweden

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Abstract

Decline of the oak forests decline in southern Sweden has been reported for more than two decades. Little empirical data exists, however, to study the temporal pattern of the phenomenon in detail. In this study we quantified the temporal pattern of non-windfall oak mortality by analyzing the dataset of 44 dendrochronologically dated dead pedunculate oak (*Quercus robur* L.) trees. We compared tree-ring chronologies from recently dead and living trees from the same sites (number of sites = 13) located in the nemoral and boreo-nemoral zones in southern Sweden. For each dead tree, tree-ring chronologies were analyzed for the presence of pre-death growth depressions. A growth depression was defined as a period (of one or more years) when growth remained below the 5%, 7%, or 10% quantiles of the ring-width distribution obtained from living trees for a particular year and site.

The most recent peak in oak mortality occurred around the year 2000. Growth depressions were recorded in 80% ($n = 35$) of all dead oaks and were most prominent during the 1990s. While some oaks showed an obvious reduction in growth over several decades, 51% of the dead trees had growth depression for at least 4 years prior to death. Although diameter growth rate differed between living and recently dead trees for at least 30 years, this difference started to amplify in late 1980s–early 1990s. Presence of pre-death growth depression in tree-ring chronologies implies that (a) non-windfall mortality of oak is a decade-long process and (b) the actual death events might be lagging behind the timing of the mortality-inducing factors. ANOVA revealed significant differences in tree responses to the drought year 1992. The cumulative growth increment ratio between 1992–1994 and 1989–1991, was higher in living trees than in those that had recently died. We suggest that the spring and summer drought of 1992 resulted in the mortality of oaks that was observed in southern Sweden at the end of the 20th century. If this time lag exists, it may complicate analyses of decline-related factors and the choice of appropriate actions by forest managers. We conclude that studies of oak decline may benefit from widening the time perspective to include several decades preceding the sampling year.

Keywords: Climatic variability; Dendrochronology; Disturbance; Drought; Forest health; Hardwood; *Quercus*

Introduction

Tree mortality is a part of the natural stand dynamics which leads to changes in competitive interaction among species (Bonn, 2000; Weiner et al., 2001), recruitment

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opportunities for saplings (Welander and Ottosson, 1998), and formation of the woody debris, which, in turn, may provide habitat opportunities for deadwood-dependent species (Ranius and Hedin, 2001). *Total mortality* of a tree species within a stand is frequently viewed as sum of *internal mortality* (due to competition and senescence) and *external mortality* [due to exogenous disturbance agents like wind, drought, insect outbreaks, and fires (see review in Franklin et al., 1987)]. Internal mortality has a relatively regular temporal pattern and could be predicted based on stand age, density, and species properties (Monserud and Sterba, 1999). External mortality is to a large degree a function of external factors, which are difficult to predict, e.g., maximum wind speeds in case of windstorms or water deficit during drought. The differentiation of mortality events is frequently helpful; however, actual causes of mortality and factors predisposing a tree to death are rarely identified with certainty (Thomas et al., 2002).

Causes of external tree mortality in pedunculate oak (*Quercus robur* L.) are complex and apparently involve several direct and indirect factors (Osipov and Selochnik, 1989; Thomas et al., 2002). Recent reports on decline of European oak stands suggest that the factors responsible for decreases in the crown conditions and subsequent tree death may include summer droughts (Pilcher and Gray, 1982; Epron and Dreyer, 1993; Bridge and Winchester, 2000) and winter/spring frosts (Barklund and Wahlström, 1998). Other possible factors predisposing oak to death are site conditions (Thomas and Hartmann, 1996), fungal infections (Jung et al., 1999 and references therein), insect outbreaks (Gieger and Thomas, 2002), and direct and indirect effects of nutrient imbalances in oak (Thomas and Buttner, 1998).

In this study, we analyzed timing of death events and growth pattern of oaks (i.e., pre-death) growing in pure or mixed hardwood stands in southern Sweden. Our focus was on non-windfall and non-fire oak mortality. Although windthrow can be a direct cause of oak mortality in this part of Fennoscandia (Wolf et al., 2004), it was not evident at the study sites. Fires were not recorded in the studied stands, with the exception of the site KB (Fig. 1) where the last fire occurred in 1843 (Niklasson et al., unpublished).

Since 1988 forest condition monitoring in this region has shown a decline in the health of mature oak stands (Wjik, 1989; Sonesson, 1999; Sonesson and Anderson, 2001), followed by increased oak mortality (Drobyshev, unpublished). To reveal possible causes of this phenomenon we made use of dendrochronological methods and compared annual growth records of living and recently dead trees within the same sites. Our main objectives were:

(1) to define the temporal pattern of oak mortality recorded at the studied sites,
(2) to determine if growth of recently dead and living trees was different at the same sites?
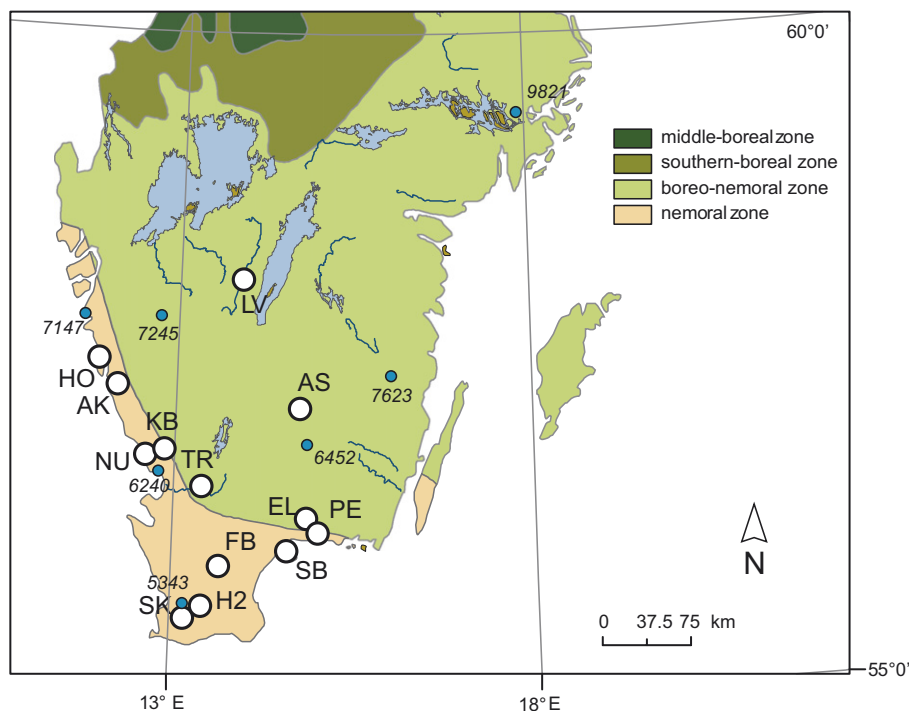(3) to determine if growth pattern of dead trees was related with the incidence of known climatic extremes?

Fig. 1. Sites with dated dead oaks (white circles, larger font size) and location of climate stations (filled circles, smaller italic font).

Methods

Study area

The field data was collected in the counties of Scania, Blekinge, Halland, Kronoberg, and Västra Götaland (Fig. 1). The mean annual temperature in this part of southern Sweden is between 5 and 8 °C. The mean temperature in January varies between 4 and 0 °C, in July between 15 and 16 °C. There is a large variation in precipitation between the western (up to 1200 mm year^{-1}) and the eastern (500 mm year^{-1}) part of the region. The typical range is within 600–1000 mm year^{-1}. West or south-west winds prevail (Raab and Vedin, 1995). Growing period with mean daily temperature above 5 °C lasts for 180–240 days (Nilsson, 1996). The soils of the studied sites bear a history of glacial dynamics and were formed on sandy and stony moraines (Fredén, 2002).

The studied region lays in the nemoral and boreo-nemoral zones (Ahti et al., 2004), where the boreal and temperate biomes prevail. Species such as Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) are the main coniferous species, while oaks (*Quercus robur* L. and *Quercus petraea* (Matt.) Liebl.), European beach (*Fagus sylvatica* L.), and small-leaved species (downy birch, *Betula pubescens* Ehrh. and quaking aspen, *Populus tremula* L.) form a typical deciduous component of forest tree vegetation.

Sampling

Dead trees were sampled in sites inventoried as a part of a larger project on oak growth and vitality in southern Sweden (Drobyshev, unpublished). For this study 13 sites were selected (Table 1, Fig. 1), where at least one dead oak tree was sampled and dendrochronologically dated. In total, 62 dead and 169 living trees were sampled. On each site a study plot was established (20×10 or 25×15 m^2), where between 7 and 20 dead and live trees were randomly sampled. Status (living/dead), diameter at breast height (130 cm, DBH), and tree height (clinometer Silva 65) were recorded for each tree. Both dead and living trees were cored (Haglöf increment corer) at breast height. Minimum DBH for a tree to be sampled was set to 7 cm. From each tree two samples were taken. In cases when the pith of the tree was not hit, the pith age was estimated by identifying the projected pith position, using increment over first five rings, located closest to the pith.

To characterize soil conditions at the sites, soil samples were taken with the Haglöf soil auger at 25–30 random points within the plot. The borer sampled to a depth of 30 cm, sub-samples from three soil layers (0–10, 10–20, and 20–30 cm) were collected for further chemical analyses. The samples were combined in field to give one sample per plot for each layer, sieved (2-mm sieve) and dried at ambient temperature (40 °C) for 2 days. The pH was measured from 20 g of dry soil, extracted in 100 ml of 0.1 M BaCl$_2$ at room temperature for 2 h. Concentrations of Al, Ca, Mg, K, Na, Mn, and Fe were determined by inductively coupled plasma analyser (Elementanalyser, model VarioMax CN, Elementar Analysensysteme GmbH, Hanau, Germany). Total nitrogen was determined by the Kjeldahl and a CR 12 method. A LECO carbon measuring instrument was used for the determination of total soil carbon (C). The concentration was normalized to the dry matter content at 40 °C. Base saturation (BS) was calculated for all three soil layers and each site. In this paper only data from the 20–30 cm soil layer is reported.

Tree-ring analysis

Cores were mounted on wooden plates and polished with 400 grid belt sander band. The cores were measured using an ANIOL measuring stage controlled by the CATRAS software (Aniol, 1983). After cross-dating, two radii from each tree were averaged into single tree series. Raw values were used for the subsequent analyses. Single-tree series were cross-dated and verified by use of signature years (Stokes and Smiley, 1968) and with the application of two computer programs: CATRAS (Aniol, 1983) and COFECHA (Grissino-Mayer et al., 1997). Individual ring-width series were normalized with both average and standard deviation being equal 1. This procedure included ring-width series from both living and dead trees.

Several methods could be employed for studying variation in tree-ring growth pattern. Change in growth over years preceding the death event can be assessed by linear regression techniques (Pedersen and McCune, 2002) and by growth-change thresholds (Lorimer et al., 1988; Lorimer and Frelich, 1989; Black and Abrams, 2003). In this study, it was reasonable to expect site-specific tree-ring growth patterns due to variation in physical properties of soils, tree age, and density of studied stands. Growth of recently dead trees was in that matter compared with growth of living trees (survivors) at the same site. The lower 5%, 7%, and 10% distribution limits for the tree-ring increments in living trees for each calendar year and site were calculated and compared with growth of recently dead trees to identify possible growth depressions occurring prior to death. The growth depression was defined as a period (of one or several years) with growth below the defined limit of the ring-width distribution obtained from living trees for the particular year. In other words, we used year- and site-specific growth data from living trees as a control to

Table 1. Characteristics of the sites where timing of tree death was determined

Site	Coordinates	Canopy composition	DBH±SD, cm	Height±SD, m	Tree age±SD, years	Soil properties		
						C/N ratio	pH	BS (%)
AS	57° 09′, 14° 46′	*Q. robur, Populus tremula*	63±12.4	23.4±3.1	156±20.4	17.9	3.46	10.2
AK	57° 15′, 12°13′	*Q. robur*	54.1±10.1	19.3±0.8	260±51.1	14.4	4.08	30.2
EL	56° 18′, 14° 53′	*Q. robur*	30±7.2	21.2±3.6	99±14.0	35.9	4.29	8.41
FB	55° 54′, 13° 38′	*Q. robur, Fagus sylvati*ca.	38±5.2	18±2.1	107±3.2	15.8	4.17	13.0
H2	55° 34′, 13° 26′	*Q. robur*	18±2.9	13.1±2.2	35±1.7	13.6	4.20	17.4
HO	57° 29′, 11°58′	*Q. robur, Acer platanoides,. P. tremula*	53±26.6	—	202±89.0	—	—	—
KB	56° 47′, 12° 51′	*Q. robur, F. sylvatica, Carpinus betulus*	28±14.3	15.5±3.6	139±61.5	26.0	4.13	6.4
LV	58° 07′, 13° 56′	*Q. robur, Pinus sylvestris*	40±19.4	17.5±2.3	159±52.2	15.4	4.10	10.0
NU	56° 49′, 12° 38′	*Alnus glutinosa, Q. robur, Fraxinus excelsior*	46±16.4	23.2±2.9	131±23.1	19.6	3.87	6.2
PE	56° 15′, 14° 58′	*Q. robur, F. sylvatica, P. tremula, Betula pubescens, Picea abies*	33±13.8	22.2±5.5	109±16.9	19.8	4.07	13.3
SB	56° 01′, 14° 41′	*Q. robur, F. sylvatica*	64±31.0	20.9±1.2	91±32.0	13.7	4.08	19.6
SK	55° 32′, 13° 14′	*Q. robur, F. sylvatica, P. abies, C. betulus*	74±37.6	22.6±3.4	134±75.2	14.6	3.53	15.5
TR	56° 32′, 13° 26′	*Q. robur*	28±6.7	18.4±2.2	130±5.3	48.8	4.43	6.64

Age was determined at breast height. Soil property values refer to the uppermost 20–30 cm of mineral soil. BS refers to base saturation. No soil or tree-height data was available for the HO site.

identify growth depressions in dead trees. Even if growth of living trees on a site during certain year decreased, growth of dead tree for same year had to remain below distribution limits (10%, 7%, or 5%) of this decreased growth to be recognized as the growth depression. Because growth of living trees was the reference, no growth depressions could be identified for living trees. Such approach allowed us to date the onset of site-specific growth depression in dead trees, estimate its duration, and to evaluate how timing and duration of identified growth depressions varied depending on the distribution limit set.

All ring-width series from dead trees were rearranged and averaged to represent growth pattern on the time-to-death scale. Prior to this step, ring-width series were transformed in ARSTAN program (Grissino-Mayer et al., 1997) to obtain the first-order residuals. To detect the timing of significant departures of this chronology from regional chronology of living trees, bootstrap method was used (Efron and Tibshirani, 1994). Values of tree-ring index of living trees were randomly selected for the period between 1970 and 2000. Same period covered mortality events, dated in the studied oak trees. The process was repeated 500 times to produce an empirical distribution of tree-ring widths for each year of the period. The variation in tree-ring widths of recently dead trees was finally compared with the bootstrap-derived distribution of living trees.

Two-factor nested ANOVA design was used to confirm differences in DBH and age between living and dated dead trees. We assumed that recently dead trees grew until the moment of sampling with the average tree-ring increment for the particular site. Specifically, we added a number of average diameter increments of living trees from a site to diameter of dead trees. This number was the difference between the year of sampling (2002) and the year of death event dated dendrochronologically. Such adjustment made comparison of diameters and age between living and dead trees within each site possible. To check for the differences in age, variables "*Age*" and "*Tree Status*" (dead or alive) were nested within factor "*Site index*". Similarly, for the differences in diameters, factors "*DBH*" and "*Tree Status*" (dead or alive) were nested within factor "*Site index*". To ensure normal distributions of age and DBH, these variables were log-transformed. Same design was used for comparison of growth responses between living and recently dead trees ("*Tree Status*" being nested within factor "*Site index*"). For the analysis only sites where number of successfully dated dead trees was three or higher, were selected ($n = 5$). Piecewise linear regression with the breakpoint determined by the Quasi-Newton method (Darlington, 1990) was used to determine if differences in the growth between living and recently dead trees varied between 1970 and 2002.

Results

In total 62 dead trees were sampled, out of which 44 trees (71%) were dendrochronologically dated. After adjustment of growing seasons between living and dead trees, was DBH of the dead trees significantly lower compared to living trees ($p < 0.001$, $F = 4.37$, df $= 8$). At the same time, mean age of those groups did not differ significantly ($p = 0.292$, $F = 1.22$, df $= 8$). Most of the trees died in the middle and late 1990s (Fig. 2), the most pronounced peak in death dates was observed in 1999.

Identification of pre-death growth depressions in dead trees was difficult because of specific growth patterns. Although depressions were clearly observable in some trees, they were difficult to locate in others. A number of depression starting dates could be suggested (Fig. 3). Depressions were therefore identified with comparison of past growth in dead and living trees for respective calendar years. Half of all dead trees (51%, with 5% threshold) indicated growth depression for at least 4 years prior to death, with some oaks showing reduced growth over a period of several decades. About 26% of all trees (given 5% threshold) showed growth depressions during 1–3 years prior to death, while no growth depression was detected in 21% of all dated dead oaks.

Growth depressions were mostly observed during the last decade of the century irrespective of the chosen growth thresholds (Fig. 4). Considering thresholds of 7% and 10%, majority of depressions were recorded since first half of the 1990s. In general, choice of a particular threshold (5%, 7%, or 10%) did not affect the results significantly.

Averaged tree-ring series on the time-prior-to-death scale showed that dead oaks experienced at least several decades-long growth depression before the eventual death event (Fig. 5A and 5B). Eight years prior to death event, average ring increment of recently dead trees was below lower 2.5% of the ring-width distribution of living trees at the same sites. On a calendar year time
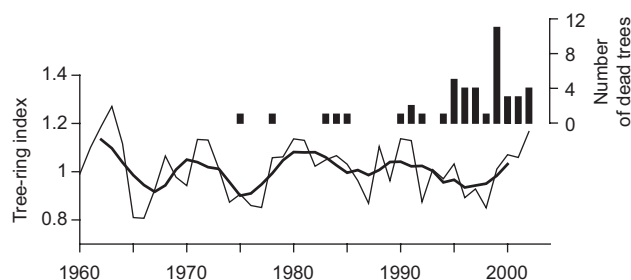

Fig. 2. Pattern of oak mortality as revealed by dendrochronological dating of dead oak trees ($n = 44$) from 13 sites in southern Sweden (see Fig. 1). Mortality pattern was superimposed over 5-year running average of regional oak chronology for same region (thick line, $n = 675$; Drobyshev, unpublished).
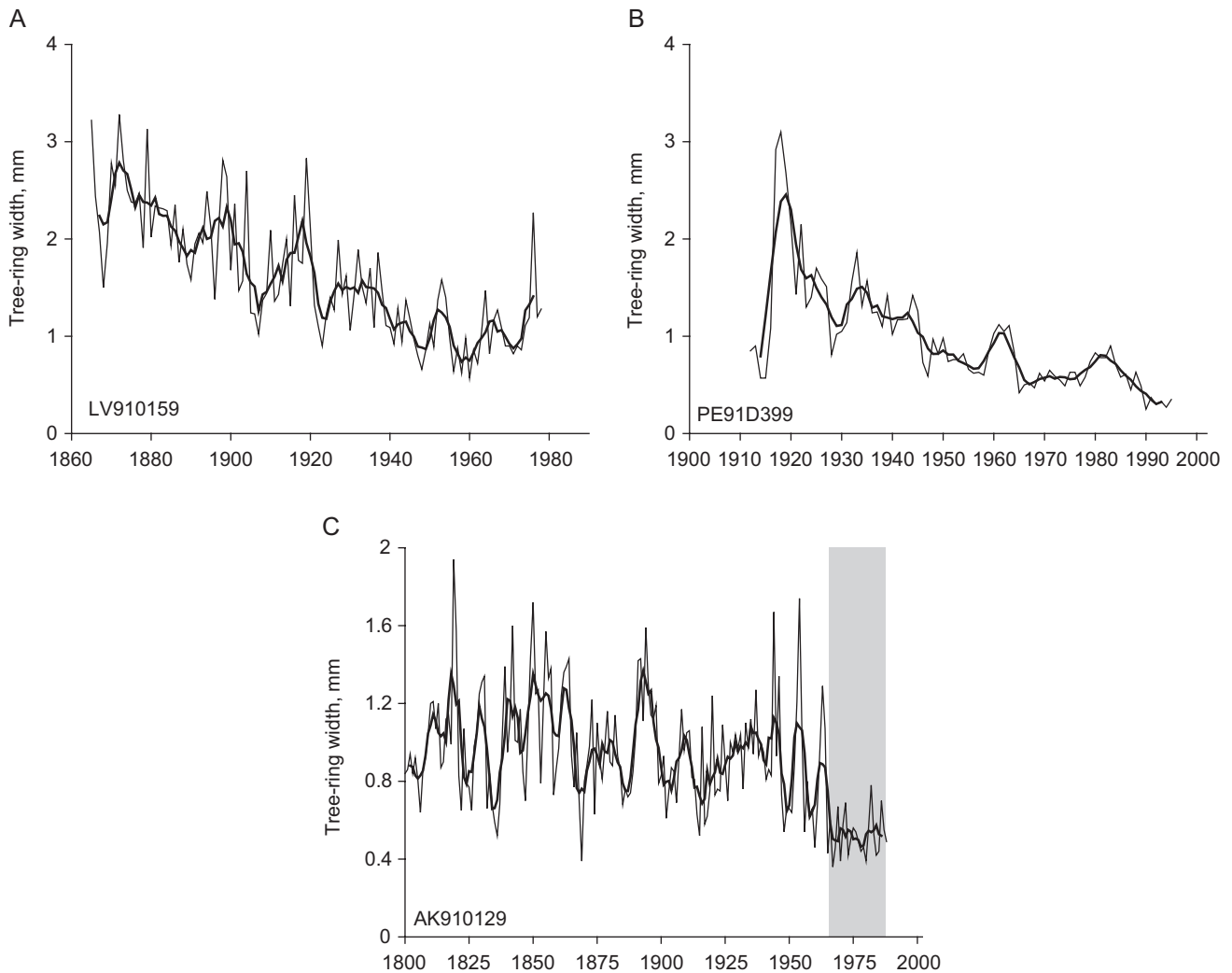
Fig. 3. Examples of chronologies from three dead trees (id *LV910159*, *PE91D399*, and *AK910129*), showing difficulties in identifying growth depression. (A) Growth pattern without clear pre-death growth depression. (B) Growth pattern with a number of periods with decreased growth. (C) Chronology with a clear growth decrease in last 15 years of tree's lifespan (shaded area). All presented curves are raw (untransformed) with 3-year moving average (thicker line) superimposed over the raw chronology.

scale (Fig. 5B), growth of recently dead trees was found below the one for living trees for at least 30 years (1972–2002, Table 2). It decreased considerably in the second half of 1990s, when differentiation in growth became even more evident. Piecewise linear regression revealed that since the late 1980s the difference in growth rate between living and recently dead trees started to increase (Fig. 5C). Two-factor nested ANOVA confirmed significant differences ($p = 0.024$, $F = 2.77$, df $= 9$) in tree growth response during the drought in 1992. In a sitewise comparison, increment ration between the periods 1992–1994 and 1989–1991 was higher in living than in recently dead trees (Fig. 6). Increments were normally distributed ($p = 0.15$ and $\chi^2 = 10.78$ given 20 as number of classes).

Discussion

Decline in crown conditions and increased mortality of pedunculate oak has been reported in southern Sweden since 1980s (Barklund and Wahlström, 1998; Wjik, 1989; Sonesson, 1999; Sonesson and Anderson, 2001). Dating of dead oaks in this study suggests that the peak of mortality was at the end of the 20th century (Fig. 2). Although this may well represent more regional pattern of oak mortality, we express caution in interpreting results in such a way. Most of the sites included in this study were managed forest stands where dead trees are commonly removed during thinning operations (Bengt Nihlgård, personal communication; Fuhrer, 1999), which was in line with our own field observations. Since only dead trees, laying or standing
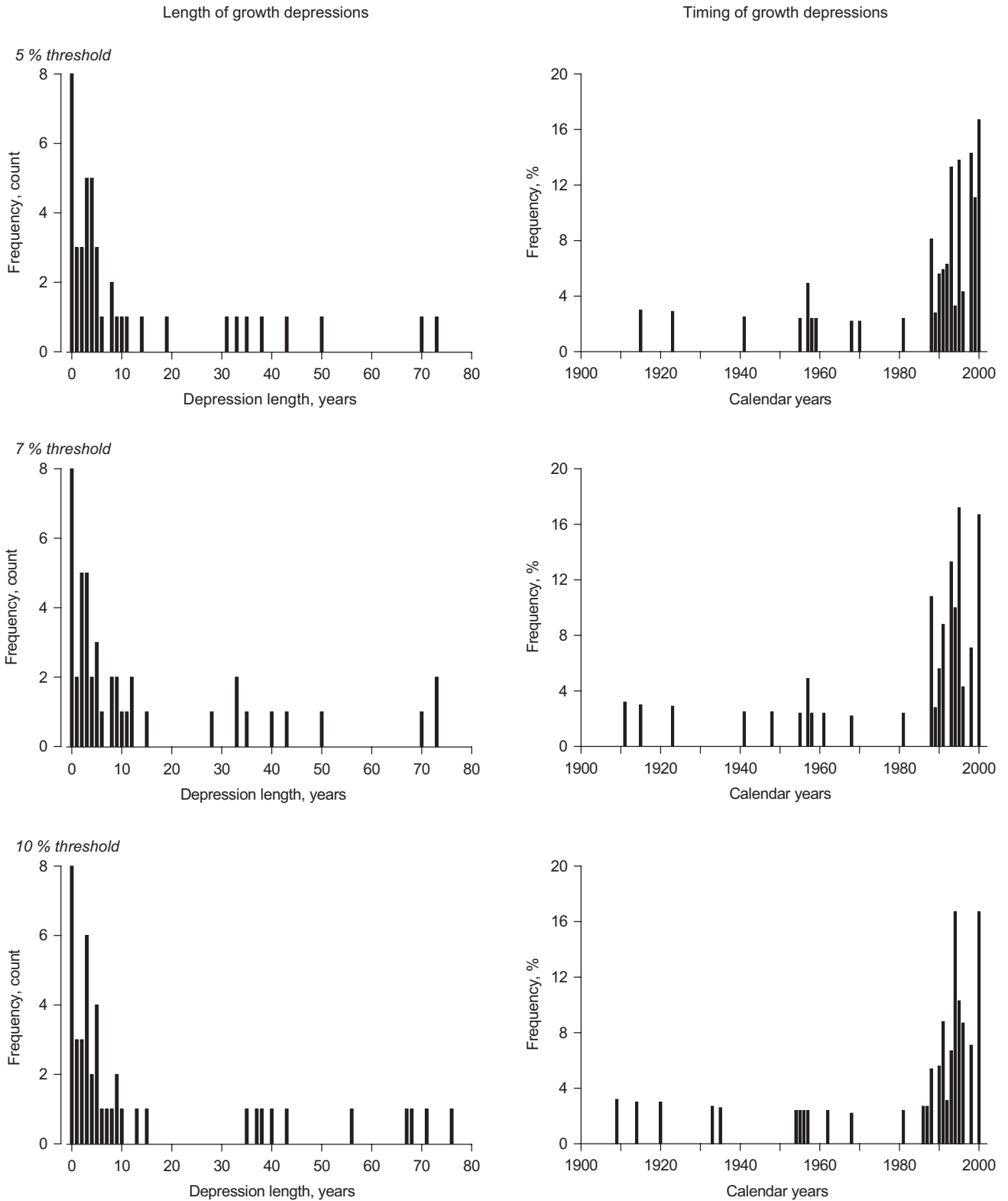
Length of growth depressions

Timing of growth depressions

5 % threshold

7 % threshold

10 % threshold

Fig. 4. Length and timing of growth depressions for dead oaks. Depression was defined as a period of growth below certain threshold calculated from the ring increment data in living trees. Three thresholds were selected as the lower (5%, 7%, and 10%) limits of ring-width distribution for every particular year. Frequency of depression is the percentage of trees that started a growth depression in a certain year, weighted with the number of curves covering particular calendar year.
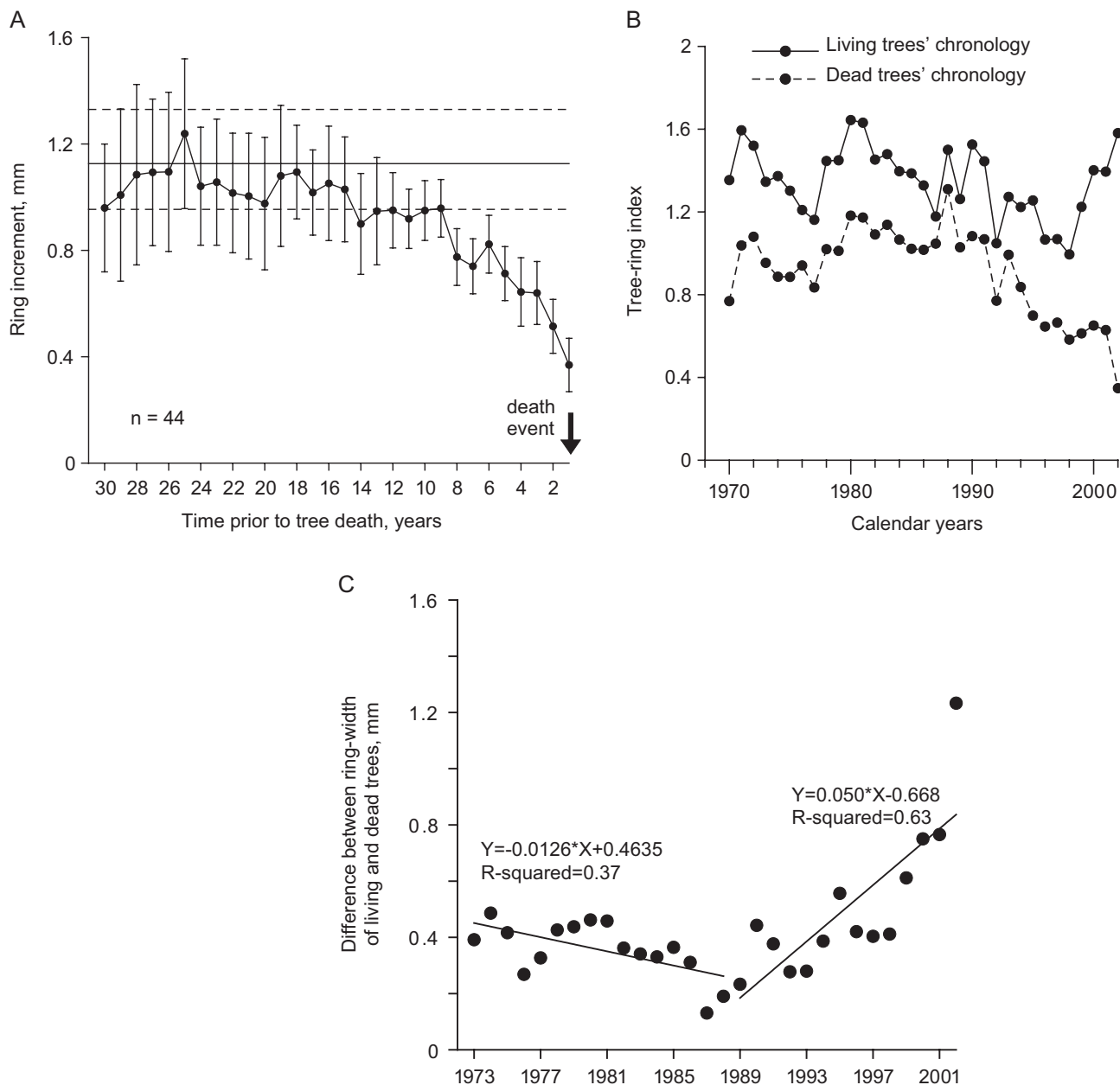
Fig. 5. Growth pattern of recently dead trees. (A) Change in ring width of the oak trees over the last 30 years preceding the death event ($n = 44$). Vertical bars denote 0.95 confidence intervals, dotted lines refer to the bootstrap-generated 2.5% and 97.5% confidence intervals for the ring increments of all sampled trees (dead and alive) from the sites with dead trees during the last 30 years since death event or the date of sampling (number of single tree rings = 2734). Solid horizontal line refers to the average ring width (1.13 mm) for all tree rings measured. Error bars represent 95% confidence limits for the distributions of ring widths in dead trees for each year. (B) Chronology of living and dead trees along calendar scale. The number of trees contributing to the dead tree's chronology decreased over time due to oak mortality between 1970 and 2002 (Fig. 2). Significant growth differences between single years are shown in Table 2. (C) Differences between ring width of living and recently dead trees for the same calendar years as a function of time. Results of piecewise linear regression with breakpoint (calendar year 1989) identified by Quasi-Newton method. Total amount of explained variation in dependent variable is 86.7%. On all figures tree-ring data was pooled for all sites.

within the stand, and not oak stumps (with missing outermost rings and due to this not suitable for the dating) were sampled and dated, the picture of oak mortality obtained in this study (Fig. 2) may over-estimate the more recent mortality in relation to

mortality in early 1990s or previous decades. There is, however, data indicating an increase in oak mortality in southern Sweden. A large-scale inventory of oak and beech forests, carried out by the Regional Forestry Board in this region over 1988–1999 (Sonesson, 1999),

Table 2. Ring-width comparison of living and dead trees at different intervals after tree mortality – results of Mann–Whitney tests

Time lags	Z	p-level
1	8.82	0.00
2	7.06	0.00
3	6.19	0.00
4	5.68	0.00
5	5.00	0.00
6	3.84	0.00
7	4.14	0.00
8	4.01	0.00
9	3.00	0.00
10	2.72	0.01
11	2.92	0.00
12	2.31	0.02
13	2.54	0.01
14	3.00	0.00
15	1.94	0.05
16	2.06	0.04
17	2.29	0.02
18	2.00	0.05
19	2.12	0.03
20	2.29	0.02
21	2.44	0.02
22	2.47	0.01
23	2.53	0.01
24	2.37	0.02
25	1.04	0.30
26	1.84	0.07
27	1.98	0.05
28	2.01	0.04
29	2.24	0.02
30	2.58	0.01

Increments of dead trees were pooled to account for the time lag since death events (1–30 years). Dataset of living trees included trees at the sites containing dead oaks and covered the period 1970–2002.

Fig. 6. Changes in tree-ring increment after the drought in 1992. Data shown, represents mean proportions of cumulative ring width for the periods 1992–1994 and 1989–1991. Filled circles represent living trees and open circles represent recently dead trees. Bars represent the standard error. Labels refer to the number of trees. Sites dated after 1994 with at least three dead trees are shown. Nested ANOVA confirmed significant differences between the increment of living and recently dead trees, with $p = 0.024$ ($F = 2.77$, df = 9).

has shown an increase in oak mortality from 0.2% during 1988–1993 to 0.6% during 1993–1999. This was calculated from taking the mean percent of the total number of trees in 265 stands, between 60 and 120 years of age, that died annually. These southern Swedish values, however, fell well below average mortality rates (1.9 ± 1.75SD) annually reported for oak in other European studies (Drobyshev, unpublished).

In our study the dead trees had lower DBH than living oaks during the same growth period, even after adjusting for the difference in number of growth seasons between dead and living trees. This suggested that competition among trees could be a factor predisposing trees to decline (Manion, 1981). For oak, indeed, such non-wind mortality has been shown to be size-dependent (Wolf et al., 2004). Since in the studied stands oaks occupied different canopy strata, this effect could be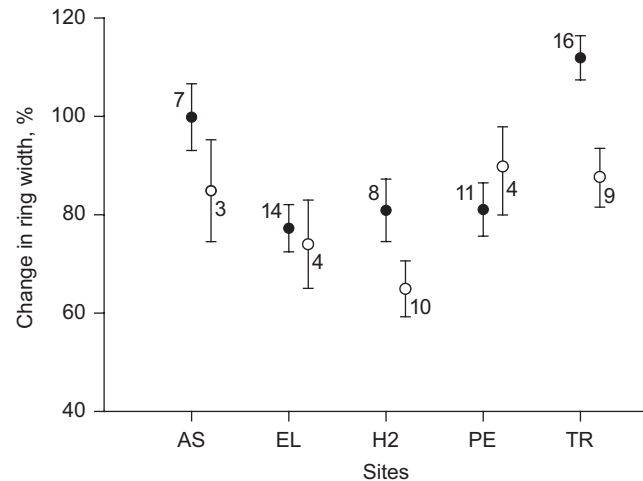 of relevance. Oak is a rather shade-intolerant species (Grime et al., 1988), the shading of trees' crown, which in closed canopy forests is inversely proportional to the size of the trees, can increase their mortality. However, age did not differ among dead and living trees, indicating that dead oaks belong to the same age cohort as the living oaks.

Growth depressions predating oak death appear to be a common feature in southern Sweden (Fig. 4), despite variation in the growth pattern of single trees (Fig. 3). Half of the oaks (51%, with 5% threshold) expressed heavily reduced diameter growth for at least 4 years prior to death (Fig. 4). Although diameter growth rate differed between living and recently dead trees for at least 30 years (Table 2), this difference started to amplify in late 1980s–early 1990s (Fig. 5C). Oak tree death typically occurred 8–9 years after a strong growth depression in ring width, where 95% of trees did not reach the lower 2.5% limit of ring-width distribution of living trees. Similar growth declines have previously been noticed in other oak species prior to tree death. For northern red oak (*Q. rubra* L.) Tainter et al. (1984) reported growth rate declining 60 years before death event. Tree-ring records from the Midwestern oak species (*Q. alba* L., *Q. prinus* L., *Q. stellata* Wangenh., *Q. coccinea* Muenchh., and *Q. velutina* Lam.) in USA revealed, that trees had suppressed growth over two decades before death event (Pedersen, 1998). Results of our study, therefore, support the view on the oak mortality as a decade-long process, which may reflect the history of regional environmental variation.

Presence of prior-to-death growth depression in tree-ring chronologies implied that the actual deaths might be lagging after mortality-inducing events. While most of the oak mortality took place in the second half of the 1990s, onset of growth depressions was mostly associated with the first half of the same decade (Fig. 4). This timing of growth depression was most recognizable while considering "the most sensitive" threshold of 10% (Fig. 4). It appears possible that timing and intensity of weather extremes commonly associated with periods of unfavorable growth conditions could shape the pattern of oak mortality.

Chronologies of recently dead trees (Figs. 5A and 5B), timing of growth depressions (Fig. 4), and differences between ring widths of living and recently dead trees (Fig. 5C) indicated that the drought in 1992 in southern Sweden, possibly played a role. During that year, a precipitation anomaly in late spring and early summer coincided with above-average temperatures for the same time (Karlström, 1993; Fig. 7). Although oaks could sustain periods of prolonged drought due to a complex system of stomatal (Dickson and Tomlinson, 1996) and non-stomatal responses of carbon fixation (Epron and Dreyer, 1990), it is sensitive to lack of precipitation in early summer (Bridge and Winchester, 2000; Siwecki and Ufnalski, 1998).

Ratio between cumulative pre-drought (1989–1991) to post-drought (1992–1994) increments declined significantly less in living than in recently dead trees (Fig. 6), suggesting that drought could act as a triggering factor predisposing trees to growth declines and subsequent mortality. Drought could also magnify stress effect of other factors, including pathogens (Jung et al., 1996; Siwecki and Ufnalski, 1998; Jonsson et al., 2003), insect defoliators (Ilyushenko, 1989), competition interactions within stand (Ståål, 1986), and other weather extremes (Barklund and Wahlström, 1998). An interesting interaction between increased mortality and two drought events has been reported in Appalachians where dieback of red oak (*Q. rubra* L.) during the drought period in the 1970s was, in part, related to a prior severe drought in 1925 (Stringer et al., 1989; Tainter et al., 1990).

The limited number of oaks dated made difficult to confidently link oak mortality in southern Sweden with a particular environmental event in the past. Yet, our results indicate the possible effect of drought events in decline of oak. This is in line with conclusions drawn in other European (Selochnik, 1989; Siwecki and Ufnalski, 1998; Bridge and Winchester, 2000) and North American studies (Stringer et al., 1989; Clinton et al., 1993; Faberlangendoen and Tester, 1993; Pedersen, 1998). We speculate that the effect of drought manifests itself as a growth depression followed with some time lag with death. Such time lag may complicate analyses of decline-related factors and choice of appropriate actions by forest managers. We conclude that studies of oak decline
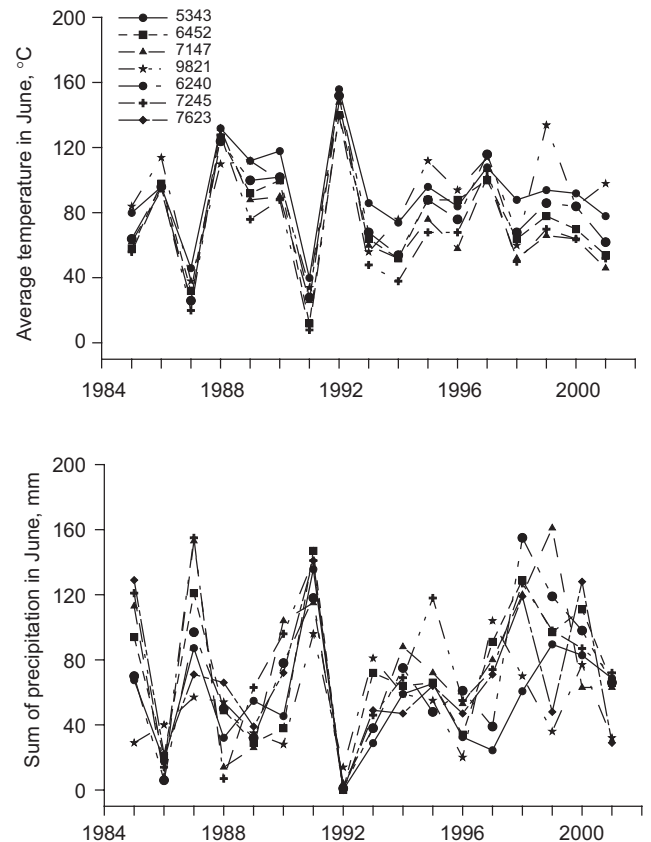

Fig. 7. Average monthly temperature and total monthly precipitation in June at several climate stations in southern Sweden during the period 1985–2001. Station codes: 5343 – Lund; 6452 – Växjö; 7147 – Göteborg; 9821 – Stockholm; 6240 – Halmstad; 7245 – Borås; 7623 – Krokshult. See Fig. 1 for station locations. Data is from the NordKlim database (Tuomenvirta et al., 2001).

phenomena may benefit from widening their time perspective to include several decades preceding the year of sampling.

Acknowledgments

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