The effect of severe ground frost on Scots pine (*Pinus sylvestris*) trees in northern Finland and implications for palaeoclimate reconstruction

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A severe frost event in the winter of 1986/1987 that resulted in widespread defoliation in northern Finland was used to test the influence of such growth disturbances on tree ring parameters commonly used for palaeoclimate reconstruction. In mature pine trees there was no effect on ring widths, latewood densities or on stable carbon isotope ratios. In young trees, however, the effect was immediate and prolonged, with a measurable increase in water stress for two years and a suppression of ring widths lasting for 6 to 7 years. There was no effect on latewood density. Where pine tree ring chronologies are used to reconstruct summer temperatures, the common practice of ignoring the juvenile years should ensure that severe frost events do not bias the reconstructions. However, extreme events may be important for understanding changes in forest dynamics, and changes in the magnitude, and frequency of such events may be important signals of human impact. The sensitivity of young pines makes them a potential archive for reconstructing past changes in growth disturbance events such as severe ground frosts.

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Introduction

Trees provide one of the best natural archives of information on past fluctuations in climate and they have been relied upon heavily in quantifying the magnitude of anthropogenic climate change (Mann et al. 1999; Houghton et al. 2001). In the northern boreal zone, summer temperature is the most important factor influencing tree growth (Hustich 1948; Mikola 1950; Briffa et al. 1990; Briffa 1994; Lindholm 1996; Lindholm et al. 1999; Jalkanen & Tuovinen 2001; McCarroll et al. 2003; Helama et al. 2004; Tuovinen 2005), so that periods of low growth in the past are generally interpreted as having had cool summers.

However, in addition to the importance of temperature, many other environmental factors affect tree growth, mainly through three primary physiological processes: photosynthesis, transpiration, and the uptake of nutrients and water. Low stemwood production per unit of foliage has, for example, been associated with the inability of trees to accumulate reserves or to produce defensive compounds (Waring 1987; Kaufmann 1990). These abiotic or biotic factors may weaken the tree, decreasing growth in the following growing season(s) so that it becomes visible in the tree-ring chronology as a short-term decline. These declines in the tree-ring chronology are easily misinterpreted.

Environmental factors affect, directly or indirectly, not only the aboveground parts of trees but also the roots and the entire rhizosphere. If the root system is disturbed, it may damage not only the health of the tree but also its growth. Even in cold climates the hardening of roots is weaker than that of needles and shoots, so that temperatures of –10 to –20°C may cause root injuries in Scots pine seedlings (Lindström & Nyström 1987; Sutinen et al. 1996). According to Korotaev (1994), Scots pine roots can resist temperatures down to –28°C, whereas needle and shoots are hardy to between –50 and –70°C in winter (Sakai & Okada 1971). Ground temperatures below –28°C can easily be reached when the soil is not insulated by snow, so root damage due to severe ground frost, which causes defoliation, is a potential source of confusion in interpreting tree ring chronologies from boreal forests.

The impact of frost-induced root decline, and ensuing defoliation, on commonly measured tree ring parameters can be tested by examining the impact of a well known severe event that occurred in the winter of 1986/1987. An unusually warm autumn melted the protective cover of snow so that the extreme cold of winter was able to penetrate the soil, damaging the fine root network (Kullman 1989, 1991; Josefsson 1990; Ritari 1990; Jalkanen et al. 1995). In the following summer (1987) defoliation was evident in northern Finland and Sweden both on spruce (*Picea abies* (L.) H. Karst.) and pine (*Pinus sylvestris* L.) (Jalkanen 1988; Kullman 1991, 1997). Pines lost an average of 2.5 and a maximum of five sets of their oldest needles (Jalkanen 1998). The needle loss was most severe on dry pine heaths, though even there only a few trees died due to the phenomenon (Kullman & Högberg 1989; Jalkanen 1993). Differences between the canopy reactions of young and old trees occurred (Jalkanen et al. 1995).

The aims of this study are: (1) to test whether the extreme growth disturbance event imparts a strong signal in the proxies commonly used to reconstruct summer temperatures, including ring widths, latewood densities and stable carbon isotope ratios. And (2) to determine whether any of the proxies might provide an archive of the past frequency and intensity of extreme growth disturbance events like ground frosts. We determine the ground frost severe, when low temperature damages tree roots and affects the tree growth. Since it is known that there were differences in the canopy reaction of young (45 years in average) and mature (130 years in average) pine trees (Jalkanen et al. 1995), they are considered separately.

Materials and methods

Site description

Two sets of ten healthy looking Scots pine trees, 45 and 130 years in average age, were selected from two adjacent sites among the dominant trees at an altitude of 150 m above sea level, in the Kivalo research area of the Finnish Forest Research Institute at Vanttauskoski (66°22′N, 26°43′E), near the Arctic Circle. It is known that the defoliation occurred on this area (Jalkanen et al. 1995) but no records on the actual defoliation exactly on these pine trees are available. The site lies in the transition zone between the middle and northern boreal vegetation zones, between Ostrobothnia and Forest Lapland (Fig. 1). The climate is semi-continental, and the fine-textured sandy soils support a dry pine-heath forest (Hämet-Ahti 1988) dominated by Scots pine. Average annual mean temperature, based on the models by Ojansuu and Henttonen (1983), is –0.1°C. Mean July temperature is 14.6°C (1961–1996) and annual precipitation 540 mm. The effective temperature sum (1962–1999; thresh-

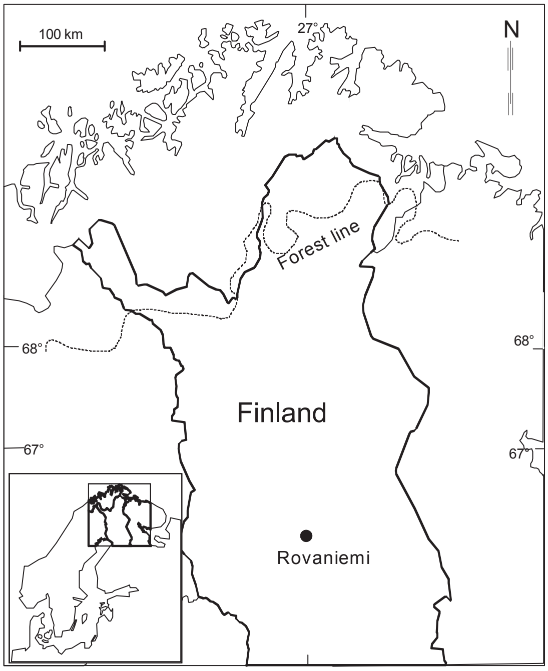

Fig. 1. Location of the Rovaniemi sampling site.

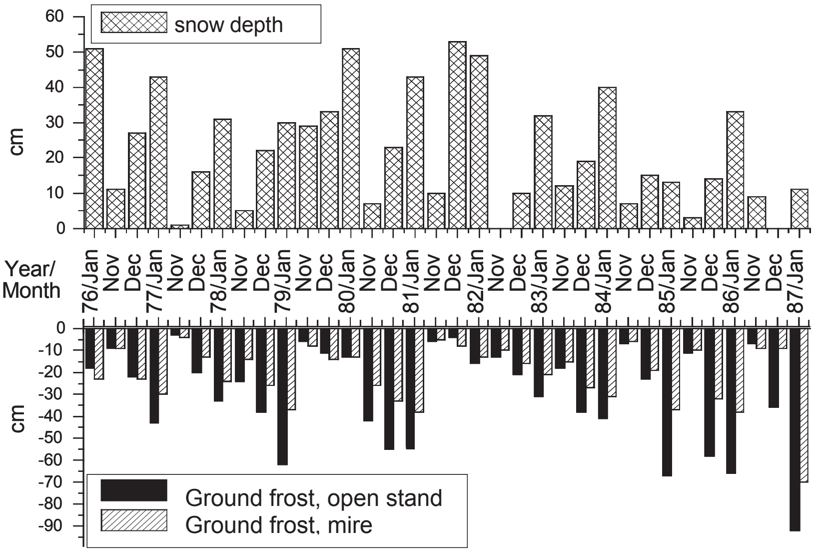

Fig. 2. The depth of snow and ground frost in January, November and December in Rovaniemi 1976–1987.

old value +5°C) is 867 degree days (Ojansuu & Henttonen 1983).

In this area, snow cover typically builds up in early November and persists until mid May (Solantie et al. 1996), effectively insulating the ground from the effects of extreme winter temperatures. However, during late November and early December of 1986, conditions were exceptionally warm and the protective cover of snow melted completely (Fig. 2). This was followed by a cold period with minimum temperatures in nearby Rovaniemi of –31.5°C in December and –39.2°C in January 1987. This combination of very low temperatures and an absence of snow cover is exceedingly rare, with a recurrence interval of perhaps once in hundred years (Solantie et al. 1996), and it resulted in rapid cooling of the soil (Jalkanen et al. 1995). In northern Finland the soil thermal capacity is so low that, in the absence of an insulating layer, minimum temperatures have a significant effect on the depth of freezing (Solantie et al. 1996). Extremely low temperatures, with a late or very thin snow cover, can lower the temperature in the upper part of coarse-textured soils down to –30°C (Jansson 1991). In 1987 the forest soils around Rovaniemi remained frozen until July (Ritari 1990), even though May and June precipitation totals were above average.

Materials

Each tree was felled, and a disk at breast height was taken for tree-ring analysis. Radial growth was measured from four radii per disk. Early- and latewood densities and widths were measured from one radius per tree using standard X-ray techniques (Schweingruber 1989). Stable carbon isotope ratios of the latewood cellulose of ten young trees and six older trees were measured using the methods described by McCarroll and Pawellek (1998, 2001). Meteorological data measured at Apukka, Rovaniemi (66°35′N, 26°01′E, 106 m a.s.l.), 35 km from the field site, were supplied by the Finnish Meteorological Institute.

Methods

The width and density chronologies (early and latewood as well as whole ring) were cross-dated and standardised using a 67% spline together with ARMA modelling to reduce autocorrelation and to pre-whiten the standardised series (Box & Jenkins 1976; Cook 1985; Guiot 1986). The program ARSTAN (Holmes et al. 1986) was employed. Chronology statistics are presented in Table 1. The stable carbon isotope series were detrended and normalised, to equalise the mean

Table 1. Chronology statistics of tree ring, earlywood and latewood widths and densities. EPS = expressed population signal.

	Trees n	Width mm Density g/c^3	Mean Sensitivity	Standard deviation	Autocorrel. Ord 1	EPS
Young trees						
Tree ring width	10	1.84	0.12	0.20	0.63	0.89
Earlywood width	10	1.13	0.11	0.15	0.51	0.87
Latewood width	10	0.30	0.18	0.20	0.37	0.90
Earlywood density	10	0.22	0.12	0.16	0.51	0.82
Latewood density	10	0.62	0.48	0.43	0.20	0.90
Old trees						
Tree ring width	10	0.99	0.20	0.18	0.65	0.88
Earlywood width	6	0.61	0.15	0.21	0.59	0.85
Latewood width	6	0.28	0.22	0.26	0.43	0.86
Earlywood density	6	0.29	0.16	0.15	0.17	0.76
Latewood density	6	0.72	0.59	0.51	0.10	0.91

and variance of the results from the young and old trees. This is necessary to remove the influence of the juvenile effect, which imparts a rising trend in the results from young trees (McCarroll & Loader 2004).

Results

Mature trees

The effects of the winter frost were very obvious in the summer of 1988, with widespread defoliation of pine trees of all age classes, so it is remarkable that there is almost no effect on the measured tree ring parameters from the mature trees. Ring widths were unaffected, with both annual and widths recording higher values than before the frost event. The rise and fall of the ring width curve between 1987 and 1990 mirrors the fluctuations in mean July temperatures, and there is no evidence of any aberrant behaviour. The stable carbon isotope ratios similarly show no effect. At this site, the stable carbon isotope ratios are controlled mainly by moisture regime (McCarroll & Pawellek 2001), with summer humidity (mean of June and July) and antecedent rainfall (February to July) explaining more than 47% of the variance in $\delta^{13}C$. The relationship between summer temperature and $\delta^{13}C$ is very weak and not statistically significant ($r = 0.2$, $p > 0.05$). The stable isotope ratios from the mature trees in the years 1987 to 1990 lie very close to the values that would have been expected given the relative humidity and antecedent moisture conditions. They do not form residuals in the regression model and there is no indication of any increase in moisture stress. The only identifiable response in the mature trees is an increase in earlywood density in the event year, which persisted until 1990. However, the expressed population signal for the earlywood density results (0.76) falls well below that normally required for any palaeoclimate reconstruction, so these results must be treated with caution. Latewood density values show no response.

Young trees

In marked contrast to the mature trees, the young trees show a clear and persistent response to the severe frost event. The first evidence of unusual behaviour occurs in the stable carbon isotope ratios in the two years immediately after the harsh winter. In comparison with the rest of the series, the isotope values for these years are not anomalously high, but when compared with the results obtained from the mature trees they stand out as clear positive residuals, indicating higher than expected moisture stress. This is consistent with damage to the fine root network. By 1989 the isotope ratios had recovered and thereafter they mirror those obtained from the mature trees.

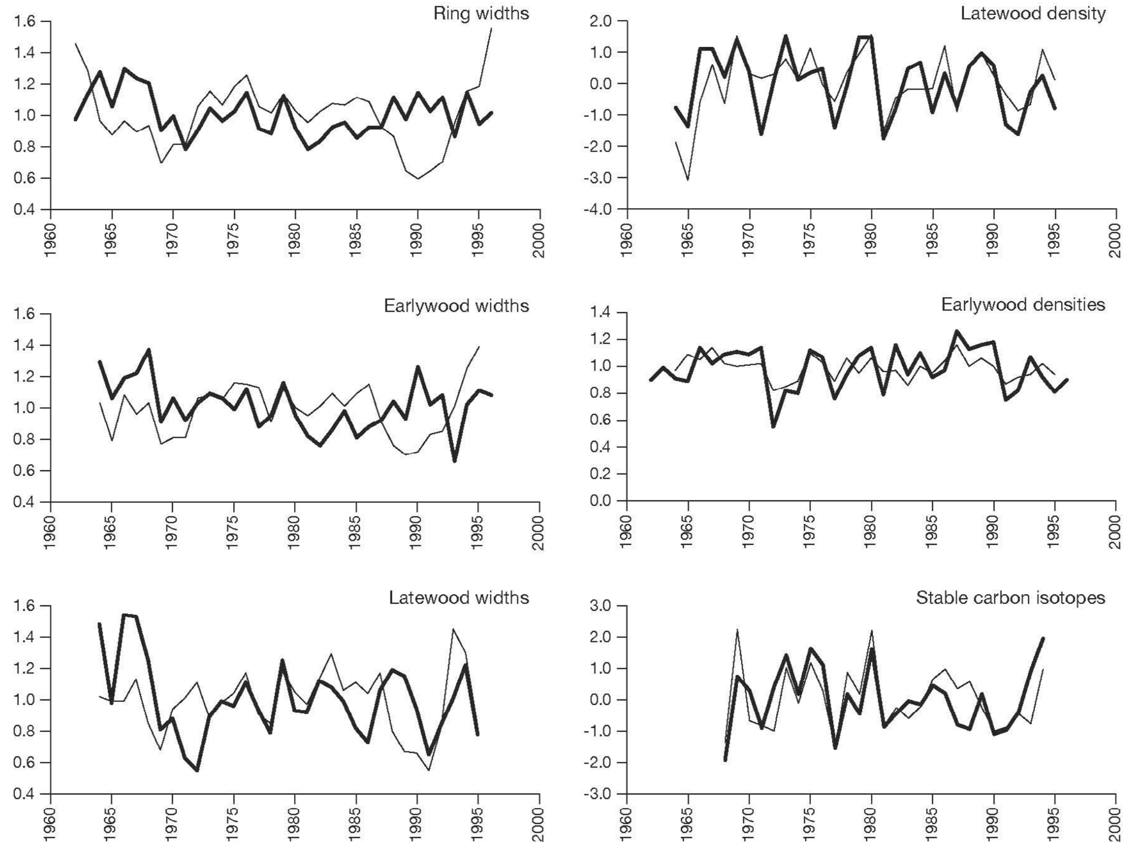

Fig. 3. Comparison of tree ring parameters from young (thin line) and mature (thick line) pine trees. The mean and variance have been equalised for ease of comparison.

The most marked response occurs in the ring widths. Before the frost event the average indexed radial growth of young and mature Scots pine (Fig. 3) fluctuates in parallel (r = 0.67, p = 0.45). After 1987, however, the radial growth of the mature trees continued at a high level, whereas that of the young trees declined immediately and rapidly. The minimum radial growth index was reached in 1990 and the decline and the following recovery took six to seven years (Fig. 3). The maximum response may have been delayed because stored carbohydrates were available in the summer following the disturbance, and this was complemented by the withdrawal of energy and nutrients from the older needles, before they died (Jalkanen 1998). At the turn of the decade, reserves were depleted, leading to the worst decline in radial growth, until growth recovered in the early 1990s. The decline in radial growth is apparent in both earlywood and latewood widths, with minimum values reached in 1989 and 1991, respectively. Latewood width recovered more rapidly than earlywood width, reflecting the greater importance of reserves in contributing to earlywood formation. The variance in the first eigenvector on young trees was higher after the harsh winter event than before it (Table 2), indicating that the response of the radial growth to the severe ground frost was more similar in young than in mature trees.

It is interesting to note that despite the clear influence of the frost event on both stable carbon isotope ratios and ring widths of the young trees, the maximum latewood density results show virtually no response. This is important because, of all of the proxies measured in this study, this parameter yields the highest expressed population signal

Table 2. Mean tree ring parameters and variance in first eigenvector (%PC1) of young (average age 45 years) and old (average age 130 years) Scots pines in 6-year periods prior and post the root decline in winter 1986/1987 at Vanttauskoski, Rovaniemi. The percentage indicates change in growth after the event.

	Growth width mm, density g/cc			Growth indexed			% PC1	
	1981–1986	1987–1992	%	1981–1986	1987–1992	%	1977–1986	1987–1996
Young trees								
Tree ring width	2.02	1.05	52.0	1.06	0.74	69.6	30.3	82.0
Earlywood width	1.15	0.65	55.9	1.05	0.79	75.3	41.8	77.7
Latewood width	0.36	0.21	58.6	1.11	0.78	70.7	42.4	71.6
Earlywood density	2.14	2.31	108.1	0.70	1.06	109.4	41.9	45.9
Latewood density	6.21	6.62	106.5	0.84	0.94	112.2	71.3	75.0
Old trees								
Tree ring width	0.80	0.96	121.0	0.88	1.07	122.0	48.1	30.4
Earlywood width	0.50	0.56	117.8	0.85	1.05	123.0	47.0	42.0
Latewood width	0.30	0.28	90.9	0.97	0.99	101.6	50.9	44.9
Earlywood density	2.74	2.79	101.5	0.99	1.08	109.7	46.5	47.3
Latewood density	7.35	7.36	100.1	0.98	0.99	100.5	82.0	61.2

and also the strongest correlation with summer temperature. There is an increase in earlywood density after 1987 but, as for the mature trees, this parameter yields a very low EPS and so the results must be interpreted very cautiously.

Discussion

In terms of the use of tree ring parameters to reconstruct summer temperatures in the boreal forests, the results of this study are comforting. Both ring widths and latewood densities of mature pine trees showed no discernable response to the severe frost event that occurred in the winter of 1986/1987, even though this resulted in widespread defoliation. Nor has Nöjd (1992) found any significant decline in older trees in southern Lapland in the late 1980s. Even the stable carbon isotope ratios, which at this site are sensitive to the moisture regime, showed no signs of increased moisture stress in mature trees. It would seem that tree ring width and density chronologies based on mature pine trees are likely to provide a reliable proxy for summer temperature even where severe winter ground frosts have resulted in widespread loss of older needle sets. These results confirm the wisdom of removing the juvenile portion of tree ring chronologies prior to palaeoclimate reconstruction.

However, an alternative interpretation is that the tree ring parameters measured on mature pine trees are effectively masking growth-disturbance events such as extreme ground frosts that are, nevertheless, important for understanding long-term changes in the vitality and growth dynamics of the forest as a whole. On this sampling site only the young trees record such events because they are more vulnerable and therefore more sensitive.

The root system of mature trees covers a wider area than that of young trees (Aaltonen 1920) and the most vulnerable fine roots, less than 1 mm in diameter, are deeper in the soil in older than younger trees (Kalela 1950). Ground vegetation competes with trees by taking nutrients and water from the uppermost soil layers (Kalela 1950), so following root decline the young trees are at a competitive disadvantage. Older trees also have thicker roots, so they have larger carbon storages from which to replenish the network of fine roots. Tree growth of the tree starts with the reserves left from the previous years, which might explain why the earlywood width decreased on young trees whereas the mature trees did not show any evidence of the event.

Even though severe frost events may have little lasting effect on mature pine trees in the boreal forests, their clear and persistent influence on the growth of young trees on this sampling site suggest that they may be very important in understanding changes in the forest as a whole. Changes in the frequency of such extreme events would have a large impact on seedling survival, for example, and could help to explain large changes in recruitment during cold intervals such as the Little Ice Age. Even the position of the tree limit might be partly controlled by such extremes. Kullman (1990), for example, has suggested that permafrost or recurring ground freezing partly controls the northern limit of spruce trees.

A reliable record of past growth-disturbance events due to severe ground freezing might also illuminate any increase in frequency that may have resulted either from anthropogenic climate change or from changes in land use practice. If global warming leads to warmer autumns in Fennoscandia, associated with cold winters, then the frequency of years when low temperatures are able to penetrate a thin or absent snow cover is likely to increase.

It would be particularly interesting to investigate whether changes in forest management over the last few decades, and in particular increased pressure from reindeer herding, have resulted in an increase in the severity of frost-induced growth disturbance events in the absence of any change in winter climate. Rather than taking the herds to summer pastures beyond the forest limit, reindeer are now allowed to graze in much of the northern forests all year. The result is that the thick lichen layer that previously existed is now largely absent from areas that are not actively protected. This thick layer acted to insulate the soil from extremes of temperature. Removing it also disturbs the symbiosis between trees and mycorrhizal fungi, thus influencing their vitality and perhaps resistance to extremes.

The results presented here suggest that it may be feasible to record changes in the frequency and intensity of extreme growth-disturbance events such as deep ground frosts by examining the difference in response of young and mature pine trees.

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