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Title: Connecting potential frost damage events identified from meteorological records to radial growth variation in Norway spruce and Scots pine

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advised in the statistical methods, SH advised in the tree-ring methods and TR advised in the frost damage issues. HM, PN, MT and SH provided the data. SS, HH, HM, PN, SH and TR contributed in writing the manuscript.

Key message: Conifer radial growth reductions may be related to unusual snow conditions or a mismatch between frost hardiness level and minimum temperature, but not typically to low winter temperature extremes.

Abstract: The aim of the study was to examine if temperature conditions potentially causing frost damage have an effect on radial growth in Norway spruce and Scots pine. We hypothesized that frost damage occurs and reduces radial growth after 1) extreme cold winter temperatures, 2) frost hardiness levels insufficient to minimum temperatures, and 3) the lack of insulating snow cover during freezing temperatures, resulting in increased frost and decreased temperatures in soil. Meteorological records were used to define variables describing the conditions of each hypothesis and a dynamic frost hardiness model was used to find events of insufficient frost hardiness levels. As frost damage is likely to occur only under exceptional conditions, we used generalized extreme value distributions (GEV) to describe the frost variables. Our results did not show strong connections between radial growth and the frost damage events. However, significant growth reductions were found at some Norway spruce sites after events insufficient frost hardiness levels and, alternatively, after winters with high frost sum of snowless days. Scots pine did not show significant growth reductions associated with any of the studied variables. Thus, radial growth in Norway spruce may be more sensitive to future changes in winter conditions. Our results demonstrate that considering only temperature is unlikely to be sufficient in studying winter temperature effects on tree growth. Instead, understanding the effects of

changing temperature and snow conditions in relation to tree physiology and phenology is needed.

Keywords: tree growth, tree-rings, frost damage, extreme value distributions, frost hardiness

1. Introduction

During the last century, winter temperatures in northern Europe have increased more than the annual average temperatures (IPCC 2014, Mikkonen et al. 2015). The effects of climate change are not restricted to winter time temperature only. Changes in length of snow season, snow properties and soil temperatures have also been documented and these trends are likely to continue in the future (Venäläinen et al. 2001, Helama et al. 2011, Liston and Hiemstra 2011).

In northern Europe, growing season temperature is the main factor affecting annual variations of tree growth, while the effects of winter temperatures are considered to be minor (e.g., Briffa et al. 2002). However, contradicting results regarding the effects of winter conditions have been reported. For example, several studies on Norway spruce (*Picea abies* (L.) Karst.) have shown negative correlations between radial growth and winter temperatures, suggesting that years with cold winter temperatures are associated with higher radial growth (Jonsson 1969, Miina 2000, Mäkinen et al. 2000, Helama and Sutinen 2016). These patterns appear to be species-specific, as studies with Scots pine (*Pinus sylvestris* L.) have found positive or non-significant correlations between ring-width series and winter temperatures (Jonsson 1969, Miina 2000).

The mechanisms of how low temperatures are related to radial growth are not fully understood. Connections between frost events and reduced growth have been explained by changes in resource allocation for replacing the damaged tissues, as well as reduced resource collection (e.g., reduced photosynthesis due to needle damage), which could reduce growth in the following summer (Dittmar et al. 2006, Príncipe et al. 2017). However, trees growing in cold environments are adapted to harsh winters. Therefore, the relationship between low temperatures and tree growth is not likely to be linear. Instead, growth reductions can only be expected after extreme events that exceed the conditions trees are acclimated to. This poses a challenge on the research methods, as classical statistical methods are not well suited for studying rare events (Katz et al. 2005). Statistical distributions defined by the majority of observations near the center of the distribution are not likely to describe well the characteristics of the distribution tails (i.e., minima and maxima). The statistical theory of extreme values resolves this problem, as the generalized extreme value distributions (GEV) specifically describe the form of distribution tails (Gaines and Denny 1993, Coles 2001, Katz et al. 2005).

The study of extreme and rarely occurring events is challenging also from the biological point of view and identifying biologically meaningful extremes is not straightforward (Gutschick and BassiriRad 2003, Babst et al. 2012, Frank et al. 2015). Gutschick and BassiriRad (2003) suggested that extreme events should be defined based on the acclimation capacity of the studied organism. As organism's ability to tolerate extreme conditions typically changes in time, using purely environmental variables in defining the extremes is insufficient. For example, the potential damage caused by cold temperatures depends on the frost hardiness of tree tissues (Leinonen 1996, Hänninen 2016). Late frost events in spring, when the frost hardiness of trees has already decreased, are typical causes of frost damage, and have been linked to abrupt growth declines prior to tree death (Vanoni et al. 2016). Even though the occurrences of low temperatures are expected to decrease (IPCC 2014), some studies suggest that frost damage in trees may increase with warmer springs and larger temperature fluctuations (Cannell and Smith 1986, Hänninen 1991, Augspurger 2013).

The effects of winter temperatures on boreal trees are mediated by the characteristics of the snowpack. As snow forms an insulating layer, lack of snow cover combined with freezing temperatures leads to low soil temperatures and deep soil frost (Groffman et al. 2001, Hardy et al. 2001). In both Scots pine and Norway spruce, severe soil frost conditions have been connected to needle loss and reduced growth (Tikkanen and Raitio 1990, Kullman 1991, Solantie 2003, Tuovinen et al. 2005). Helama et al. (2013) showed that low soil temperatures as well as deep snowpack in spring were associated with lower radial growth of Scots pine. Furthermore, artificially increased soil frost, especially if soil thawing in spring is delayed, has been found to be related to higher fine-root mortality (Gaul et al. 2008, Repo et al. 2014), reduced starch content in needles (Repo et al. 2011) and delayed growth onset (Jyske et al. 2012) in Norway spruce, as well as defoliation in Scots pine (Jalkanen 1993).

Our aim was to examine if exceptional temperature conditions, potentially causing frost damage to trees, have an effect on the radial growth of Norway spruce and Scots pine. In our analysis, we took into account both biological and statistical challenges in studying extreme events. We tested three hypotheses, suggesting that frost damage occurs and reduces radial growth after (1) extreme cold winter temperatures (TMIN), (2) insufficient level of frost hardiness compared to minimum temperatures (REL_TMIN), and (3) lack of insulating snow cover during freezing temperatures, resulting in low soil temperatures (FROSTSUM). The first hypothesis represents a simple extreme in temperature, whereas the two latter hypotheses also consider physiological state of a tree and the processes of the studied system. We expect the results to differ for Norway spruce and Scots pine as previous results have shown different patterns for the two species.

2. Material and methods

2.1 Data

2.1.1 Tree-ring data

The tree-ring data used in the study was compiled from previously collected Norway spruce and Scots pine data sets. In all data sets, the sampled sites were located in national parks or other unmanaged forests. In the Norway spruce data set, 47 stands were sampled from southern Finland to the Arctic spruce timberline (Fig. 1). At each site, one to two increment cores were taken at 1.3 meter height from up to 15 dominant trees. For a detailed description of the Norway spruce data set see Mäkinen *et al.* (2000) and Mäkinen *et al.* (2001). The Scots pine data set contained 20 sites in southern and northern Finland (Helama et al. 2013). The number of trees sampled per site ranged from 9 to 120, and one to two cores were taken from each tree.

Annual tree-ring widths were measured from all cores to the nearest 0.01 mm with a light microscope. Cross-dating of the ring-width series was performed visually and verified statistically using computer program COFECHA (Holmes 1983) and the *dplR* package (Bunn 2010, Bunn et al. 2015) of R software (version 3.3.1, R Core Team 2016). The samples that could not be cross-dated were excluded from the data (see Supplement 1 for the final number of trees per site).

To remove trends related to tree age and stand dynamics, we standardized the ring-width series using a spline function with 50% frequency cut-off in 67% of the length of the tree-ring series (Cook and Peters 1981, Speer 2010). Ring-width indices (RWI) were then formed by dividing the measured ring-widths with the values of the fitted spline function, and temporal autocorrelation was removed with first-order autoregressive model. After this, site-wise average chronologies were formed by calculating annual averages from all trees at a site with Tukey's biweight robust mean. Chronologies were cropped to cover years 1922-1997 (common years of all chronologies).

2.1.2 Weather data

Daily mean and minimum temperatures from four weather stations in Finland and from Karasjok weather station in Norway (Fig. 1) were used. Years 1927 and 1945 had a lot of missing values and were excluded from further analysis using the weather station data (Table 1). If daily mean temperature was not available, it was calculated from the individual temperature measurements and daily minimum temperatures using the equations of Finnish Meteorological Institute (FMI 2016). Data from the closest weather station to each tree-ring site was used in the analysis (see Suppl. 1 for details).

In addition to weather station data, gridded data of snow depth and daily mean temperature were used (Aalto et al. 2016). This data set has a resolution of 10×10 km^2 and it is available from year 1961 onwards.

2.2 Defining potential frost damage events

To test the hypotheses we used the weather data to define three variables describing conditions potentially causing frost damage to trees (referred to as "frost variables" from now on, Table 1). Minimum winter temperature (TMIN) was calculated as the minimum of daily minimum temperatures. Relative minimum temperature (REL_TMIN) was calculated as the difference between the modelled daily frost hardiness and daily minimum temperature. The frost hardiness value describes the temperature in which 50% of needle area is damaged (Leinonen 1996, see section 2.3). Frost sum of snowless days (FROSTSUM) was used to describe the variation in soil frost between years. It was calculated as the sum of daily temperature averages below 0 °C during the days without snow cover. While TMIN and REL_TMIN variables were calculated for each site by using the weather data from the closest meteorological station, FROSTSUM was calculated from the grid data (daily average temperature and snow depth), using the grid cell in which the site was located. As the grid data was only available from year 1961, the analysis using the FROSTSUM variable covered a shorter time period (1962 to 1997), whereas TMIN and REL_TMIN variables were available for the whole time period covered by the tree-ring chronologies (1922 to 1997, Table 1).

In all three variables, low values represent potentially damaging conditions to trees. For the TMIN and FROSTSUM variables, annual values covered a time period from previous year July to the growth year June, while in the REL_TMIN variable only time period from January to May was considered (Table 1).

2.3 Frost hardiness model

The daily level of frost hardiness was calculated with a dynamic needle frost hardiness model developed by Leinonen (1996) for Scots pine. The model output describes the temperature in which 50% of needle area would be damaged. The model uses daily mean and minimum temperature and night length as inputs to calculate the stationary frost hardiness, i.e. the target level of hardiness in the prevailing environmental conditions. The frost hardiness approaches the stationary level with the delay. Thus, the rate of change in frost hardiness is calculated from the frost hardiness of the previous day and the stationary level of frost hardiness (Fig. 2).

In order to use the model for Norway spruce, as well as different provenances of Scots pine, we made some modifications to the model. In Leinonen's model, the amount at which environmental conditions affect stationary frost hardiness is controlled by hardening competence (Fig. 2), which is determined from an annual cycle model with daily mean temperature as input. Hardening competence varies so that the effect of environmental conditions (i.e., daily minimum temperature and night length) on frost hardiness is strongest during the rest phase (hardening competence = 1) and weakest during active growth phase (hardening competence = 0). As different species and provenances within species have different annual cycles, we could not use the same annual cycle model for all of our sites. While Leinonen (1996) calculated frost hardiness for each day of the year and modelled the full annual cycle dynamically, we decided only include a time period from January to May. Similar restriction to modelled time-period was used by Hänninen et al. (2001). We assumed that in the beginning of the year trees were in quiescence and that hardening competence was 0.9. These assumptions were based on studying the frost hardiness values calculated using Leinonen's original method with the full annual cycle model. By restricting the covered time period we were able to take into account different timing of spring phenology between species and provenances without reparametrizing the whole annual cycle model.

To account for the differences in spring phenology between Scots pine and Norway spruce, as well as different Scots pine provenances, we modified the parameter controlling spring dehardening based on previous results from provenance tests (Beuker 1994). In quiescent and active growth phases hardening competence is calculated using a parameter FU_{crit} that defines the amount of forcing units (FU) needed to accumulate for bud burst to occur. We defined the value of FU_{crit} for different provenances of Scots pine and Norway spruce based on temperature sums (with 5 °C threshold) required for bud burst reported from provenance tests (Beuker 1994). First, we calculated the accumulation of FU from the beginning of year to the day that temperature sum reached the value required for bud burst in years 1950 to 2013. Then, FU_{crit} was defined as mean of these annual FU values (Supplement 2).

As the frost hardiness value for each day is calculated based on the change from the previous day, we needed to define the frost hardiness level for January 1st. We did this by starting the frost hardiness modelling from the beginning of December, assuming the frost hardiness to be equal to the stationary frost hardiness in December 1st (Fig. 3).

2.4 Defining extreme years – Generalized extreme value distributions

Generalized extreme value distributions (GEVs) were used to define thresholds for identifying years with exceptional winter conditions to which the trees would not be well acclimated to. We fitted GEVs to the three frost variables separately in each weather station (or in each site for FROSTSUM variable), using the R package *extRemes* (Gilleland and Katz 2011).

For the TMIN and REL_TMIN variables we fitted the GEVs with the block maxima approach, i.e. the variables represented an extreme within certain time window (Table 1). GEVs have three parameters, location parameter (μ), scale parameter (σ) and shape parameter (ξ). The shape parameter defines the shape of the distributions, so that $\xi = 0$ corresponds to a light tailed (Gumbel) distribution, $\xi > 0$ to a heavy tailed (Fréchet) distribution, and $\xi < 0$ a bounded (Weibull) distribution (Coles 2001, Katz et al. 2005).

Since the FROSTSUM variable is a sum of conditions within a season, the block maxima approach was not applicable with it. Therefore, we chose to use a "peaks over threshold" (POT) approach, where the extreme value distribution is fit to values exceeding a chosen threshold. These values should have an approximate generalized Pareto (GP) distribution, with two parameters, scale (σ) and shape (ξ), which have same interpretations as with the GEV distributions. In this case $\xi = 0$ corresponds to light-tailed (exponential) distribution, $\xi > 0$ to a heavy tailed (Pareto) distribution, and $\xi < 0$, a bounded (beta) distribution (Katz et al. 2005).

The extreme value distributions typically handle maximum values, and as we were interested in the minima, all distributions were fitted to the inverse values of the original variables (see Katz et al. 2005). To account for the warming trend in temperatures, we tested including year as a covariate for the GEV parameters. In total, we tested three types of GEVs: 1) no covariates, 2) year as a covariate for the location parameter, and 3) year as a covariate for location and scale parameters. We compared these three with Akaike Information Criteria (AIC, Akaike 1974), and selected GEVs without any covariates, as they had the lowest AIC values in a majority of weather stations (sites in FROSTSUM) for all frost variables.

In identifying the extreme years in each frost variables we used a ten year return level, defined from the extreme value distributions. The ten-year return level means that values lower than this level can be expected to occur on average once every ten years (Coles 2001). For the three frost variables, the ten year return level was calculated for each weather station (site in FROSTSUM) and each year exceeding this threshold was defined as an extreme year in the frost variable in question.

2.5 Statistical analysis

We fitted two linear regression models separately to all site chronologies. With the first model ("dummy model") we tested if RWIs were lower in years with low values of the three frost variables (i.e., values lower than the 10-year return level), while also taking into account the effect of summer temperature on radial growth. The first model was formulated as

$$RWI_t = \beta_0 + \beta_1 SummerT_t + \beta_2 Frost\_RL10_t + \varepsilon_t, \quad (1)$$

where RWI_t is the value of RWI chronology in year t, $SummerT_t$ is the mean temperature of June (Norway spruce) or July (Scots pine) in year t, and $Frost\_RL10_t$ is a dummy variable (0/1) describing whether the value of the frost variable (TMIN, REL_TMIN or FROSTSUM) was lower than the 10-year return level in year t.

In the second model ("slope model") we also included a continuous frost variable (TMIN, REL_TMIN or FROSTSUM) and its interaction with the *Frost_RL10* dummy variable to test if the severity of the frost conditions was related to the radial growth variation. The second model was formulated as

$$RWI_t = \beta_0 + \beta_1 SummerT_t + \beta_2 Frost\_RL10_t + \beta_3 Frost_t + \beta_4 Frost\_RL10_t\, Frost_t + \varepsilon_t, \qquad (2)$$

where $Frost_t$ was the continuous frost variable in year *t*. Logarithm transformations were tested for the continuous variables but they did not change the outcomes of the models. In both models the FROSTSUM variable was scaled to mean of zero and standard deviation of one in order to have the model coefficients in similar magnitudes as the other two frost variables. Correlations between explanatory variables in the models were low and in most cases statistically non-significant.

In order to test if the slope model had a better fit to the data compared to the dummy model, the models were compared with likelihood ratio test within each site (using R function *anova*). All analyses were conducted using the statistical software R (R Core Team 2016).

3. Results

3.1 GEVs and extreme year classification

In the GEVs fitted to TMIN and REL_TMIN variables, all shape parameters (ξ) were negative, corresponding to a Weibull distribution. In FROSTSUM variable, the shape parameter values ranged from positive to negative, indicating different shapes of distributions at different sites (see Fig. 4 for examples).

The years classified as extreme years based on the GEVs were not identical at different weather stations (Fig. 5). However, in the TMIN variable several years were consistently classified as extreme years in several weather stations, for example 1940 (4 stations), 1956 (3 stations), 1966

(4 stations) and 1987 (3 stations). In the REL_TMIN variable, there was more variation between the weather stations, whereas the extreme years for spruce and pine were very similar (Fig. 5).

In the FROSTSUM variable, gridded weather data was used instead of weather station data and, therefore, the GEVs were fitted for each site separately and the extreme years differed between sites (Fig. 6a). Per site, two to seven years were classified as extreme years (Fig. 6b).

3.2 Connections between RWI and frost variables

The connections between the frost variables and ring-width indices (RWI) showed different patterns for Norway spruce and Scots pine. In the Norway spruce dummy models, the extreme TMIN variable (i.e., $Frost\_RL10$ in Eq. 1 with TMIN as frost variable) showed positive coefficients in the majority of sites (43 of 47 sites), and it was statistically significant in the 16 of the total 47 spruce sites (all significant coefficients in northern Finland, Fig. 7). This indicates that radial growth was in fact higher after winters with exceptionally cold minimum temperature. For Scots pine, none of the coefficients for extreme TMIN variable were significant in the dummy models (Fig. 7).

The extreme REL_TMIN variable (i.e., $Frost\_RL10$ in Eq. 1 with REL_TMIN as frost variable) showed negative coefficients in the Norway spruce dummy models at 43 of the 47 sites (Fig. 5), suggesting lower radial growth in years in which minimum temperature had been exceptionally close to the modelled frost hardiness levels. However, the coefficients were statistically significant only at two sites, located in northern and central Finland. In comparison, in the Scots pine models the three sites (of total 20 pine sites) where the REL_TMIN coefficient was significant, but the effect was positive, indicating higher radial growth in those years.

The extreme FROSTSUM variable (i.e., *Frost_RL10* in Eq. 1 with FROSTSUM as frost variable) showed negative coefficients in the Norway spruce dummy models at 33 of the 47 sites (i.e., lower growth in the years with exceptionally high frost sum of snowless days), but the variable was only significant in the models of seven sites (Fig. 5). For Scots pine, the FROSTSUM variable was not significant in the dummy models at any of the twenty sites.

In the slope models, positive coefficients for the frost variables during extreme years (sum of β_3 and β_4 in Eq. 2) suggest that radial growth decreased with decreasing values of the frost variables. However, both positive and negative coefficients were found in sites where the likelihood ratio test showed a significant improvement compared to the dummy model. For Norway spruce, positive coefficients in slope models that significantly improved the dummy model fit were only found in the FROSTSUM model in six sites in northern Finland, and for Scots pine only at one site both in TMIN and FROSTSUM variables (Fig. 8). Slope models with negative coefficients (i.e. radial growth increasing with decreasing values of frost variables) were found at one Scots pine site in REL_TMIN variable and at seven closely located Norway spruce sites in FROSTSUM variable (Fig. 8). In other cases the likelihood ratio test did not show significant improvement of model fit from the simpler dummy model.

4. Discussion

Our results did not show very strong connections between radial growth and the potential frost damage events defined using meteorological data. However, our hypotheses of reduced growth after events of insufficient level of frost hardiness (REL_TMIN) and after winters with high frost sum of snowless days (FROSTSUM) were supported by the results from some of the Norway spruce sites. Reductions in radial growth were related only to those variables that took frost hardiness or snow cover into account, whereas year with low minimum winter temperatures showed statistically significant growth increases at some sites. Therefore, our results highlight that, when studying winter climate effects on tree growth, physiological and other processes affecting the studied system need to be carefully considered instead of using purely environmental variables.

While the results for Norway spruce gave some support for our hypotheses about extreme relative minimum temperatures and frost sums of snowless days being harmful for growth during the following growing season, the results for Scots pine were generally statistically non-significant or even opposite to the original hypotheses. This agrees with our original expectation of between-species differences and is in line with previous studies (Jonsson 1969, Miina 2000). The different patterns found for the two species are likely to be related to differences in winter time physiology. For example, Beuker et al. (1998) reported weaker frost hardiness of Norway spruce buds compared to Scots pine, and Linkosalo et al. (2014) showed that Norway spruce photosynthesis was reactivated during warm winter spells more readily, whereas the cold inhibition of photosynthetic light reactions was stronger in Scots pine.

The results supporting our hypotheses were statistically significant only in a minority of study sites. Therefore, conclusions about the results should be made with caution. The differences in statistical significance between the sites may be at least partly related to the spatial variability of minimum temperatures and snow cover. Due to a need for long time series the distance between some study sites and the weather stations was rather large and, therefore, the weather data is likely to be less representative of the conditions at these sites (Fig. 1, Supplement 1). In addition, the resolution of the gridded data used for calculating FROSTSUM (10 x 10 km^2) may hide local, more fine-scale variation in snow cover. Therefore, the used weather data may not accurately describe the local conditions at the study sites, especially since minimum temperatures vary locally with topographic variation and proximity of water bodies (Jarvis and Stuart 2001). It is possible that the sites showing a significant effect of the frost variables on RWI are more sensitive to frost, due to factors that were not taken into account in the statistical analysis. The different results between sites may also be related to tree age. Tuovinen et al. (2005) showed that severe soil frosts in northern Finland in winter 1986-1987 did not affect radial growth in mature Scots pines (approx. 130 years), whereas younger trees (approx. 45 years) showed increase in water stress for two years, as well as suppressed radial growth for 6 to 7 years after the exceptionally harsh winter conditions.

The way our frost variables were defined limits the type of cases included in the analysis. For example, TMIN and REL_TMIN variables only accounted for the lowest daily values within the season. However, especially in the case of TMIN it might have been also relevant to consider, for example, the length of longer time periods with low minimum temperatures. Winter conditions may also affect the growth of the following growing season in many ways that are not all included in our hypotheses. For example, warm winters may lead to respiratory losses, especially in Norway spruce, if trees initiate photosynthetic activity before sufficient availability of light (Linkosalo et al. 2014). This could be one potential mechanism behind pattern of higher radial growth after low winter temperatures, which was observed in this study, as well as in earlier studies (Jonsson 1969, Miina 2000, Mäkinen et al. 2000). However, more research would be needed to understand if this correlative pattern is related to the winter time conditions or some other factors.

To refrain from parametrizing the full annual cycle model and to reduce the potential uncertainties associated with it, we modelled frost hardiness only for a restricted time period from January to May (see Hänninen et al. 2001 for similar approach). However, events of insufficient frost hardiness may occur also if temperatures drop before trees have developed adequate hardiness levels after the growing season (Sutinen et al. 2001). For example, Mikola (1952) suggested that autumn frosts were likely a major cause for the considerable growth reductions of Scots pine in the early 20th century in northern Finland. Therefore, our results do not cover possible frost damage events occurring outside of the chosen time-frame. Further development and parametrization of frost hardiness models would demand more studies on the topic.

The effects of snowpack on trees are more complex than accounted for in the FROSTSUM variable. Especially the timing of soil thaw may be influential to tree physiology and growth. Helama et al. (2013) showed that high soil temperature and low snow depth in spring, rather than in winter, are connected to increased Scots pine radial growth of the following growing season. Similarly, artificially delayed thawing of soil frost affected the physiology of mature Norway spruce trees (Repo et al. 2007, Repo et al. 2011) and Scots pine saplings (Repo et al. 2005, Repo et al. 2008). Physiological changes were more evident when increased soil frost was combined with delayed thawing than after increased soil frost alone (Repo et al. 2011, Martz et al. 2016). In further studies, the characteristics of snowpack need to be considered in more detail.

The frost hardiness model used in the study was originally developed to describe frost hardiness in Scots pine needles in central Finland, but it has later been used also for other tree species and locations (e.g., Morin and Chuine 2014). However, the parametrization of the model for new species and even other provenances is challenging (see Hänninen 2016). In this study, we used information of temperature sums needed for bud burst in different provenances of Norway spruce and Scots pine to calibrate the parameter that controls the changes in hardening competence in spring. Despite these modifications, several parameters in the model are based on Scots pine data. Therefore, the model is likely to be less suitable for Norway spruce and also for Scots pine in northern Finland. It should also be noted, that the model describes the frost hardiness of needles, but phenology and frost hardiness differ between tree organs. For example, frost hardiness in plant roots is typically lower than in shoots (Sakai & Larcher 1987, Delpierre et al. 2016). In addition, the shape of the relationship between severity of frost damage and the difference of minimum temperature and frost hardiness is a sigmoidal curve, where the curve's slope parameter depends on frost hardiness (Leinonen 1996). Our analysis did not take this into account, as the REL_TMIN variable only considered the difference between daily minimum temperature and the level of frost hardiness.

The use of the extreme value distributions enabled us to identify the thresholds for extreme events so that they would correspond to occurrence of extreme conditions that the trees are adapted to. However, the choice of the threshold used for classifying extreme years (return level of ten years) was partly driven by practical necessities. A ten-year reoccurrence rate for an event is rather high from an evolutionary point of view, and a use of a stricter classification threshold would have been ecologically justified. Yet, to analyse the existing data we needed to define the threshold so that the number of years classified as extreme years is sufficient. To overcome this issue, we fitted the slope model, where a more flexible model behaviour was allowed with the interaction of a continuous frost variable and the dummy variable describing if a year was defined as an extreme or not. Thus, the model covered a situation where the defined threshold was too low to represent a biologically meaningful extreme and, therefore, the reduction in RWI would increase with decreasing values of the frost variables. However, with the slope model also the number of years included in the analysis is a challenge, as the study period may not necessarily contain years with truly extreme conditions in the studied variables. This is probably reflected to our results, where the slope model only supported our hypotheses on a few sites, mainly in the case of FROSTSUM variable in Norway spruce sites in northern Finland.

5. Conclusions

Our results show, that instead of extremely cold winters, Norway spruce growth is potentially reduced after events of insufficient frost hardiness or after winters with high sum of freezing temperatures without insulating snow cover. However, Scots pine growth reductions were not connected to any of the studied variables. Therefore, it seems that radial growth in Norway spruce may be more sensitive to variable winter temperatures compared to Scots pine.

Our results demonstrated that using purely environmental variables, such as minimum temperature, is unlikely to be sufficient in studying winter temperature effects on tree growth. Instead, understanding the effects of changing temperature and snow conditions in relation to tree physiology and phenology is needed.

The long time series of growth variation provided by tree-ring data is especially beneficial in studying rarely occurring events, such as frost events leading to tree damage. However, equally long time series of tree phenology data or frost damage observations are often not available. Similarly, long meteorological data records exits only for a limited number of weather stations and, thus, data on local climatic conditions at the study sites is typically lacking. Therefore, to understand the effects of changing winter conditions on tree growth, tree-ring studies should be combined with modelling approaches as well as physiological and experimental studies.

Conflict of interest

The authors declare that they have no conflict of interest.

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Figures

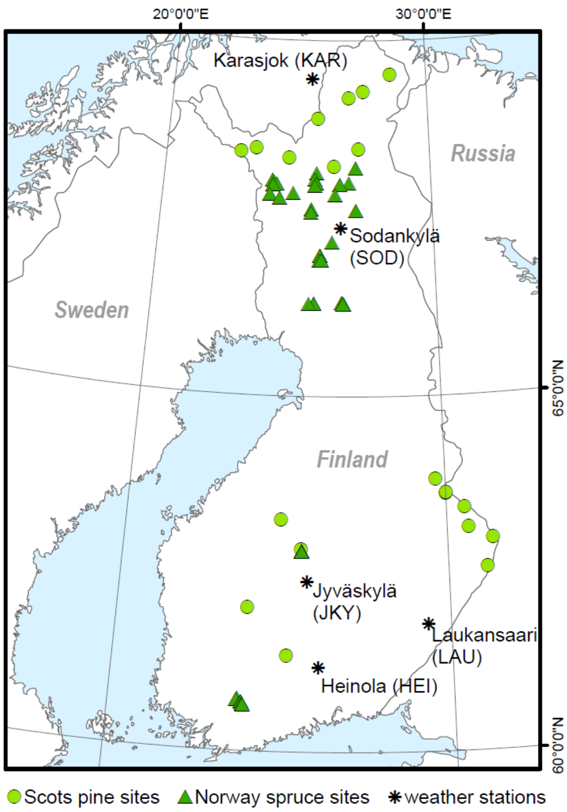

Fig. 1 Locations of the Norway spruce (triangles) and Scots pine (circles) study sites and weather stations (asterisks). Note that some of the site symbols are on top of each other (especially the spruce sites in southern Finland).

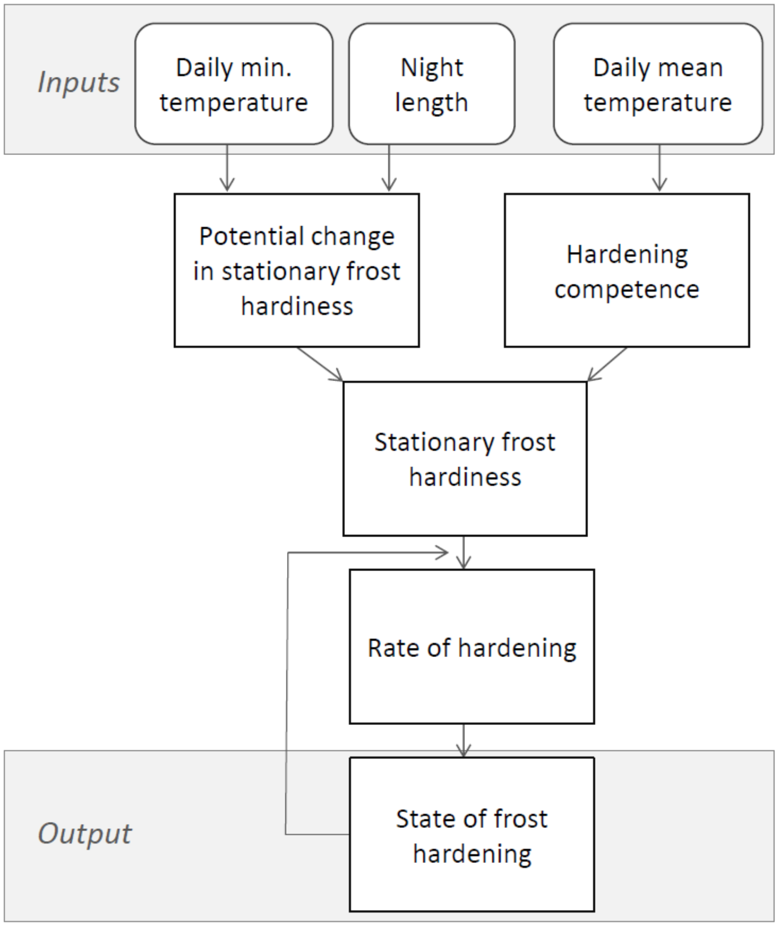

Fig. 2 Framework of the frost hardiness model (modified from Hänninen 2016). The model uses daily minimum and mean temperatures, and night length to calculate daily level of frost hardiness. A detailed description of the model can be found in Supplement 2.

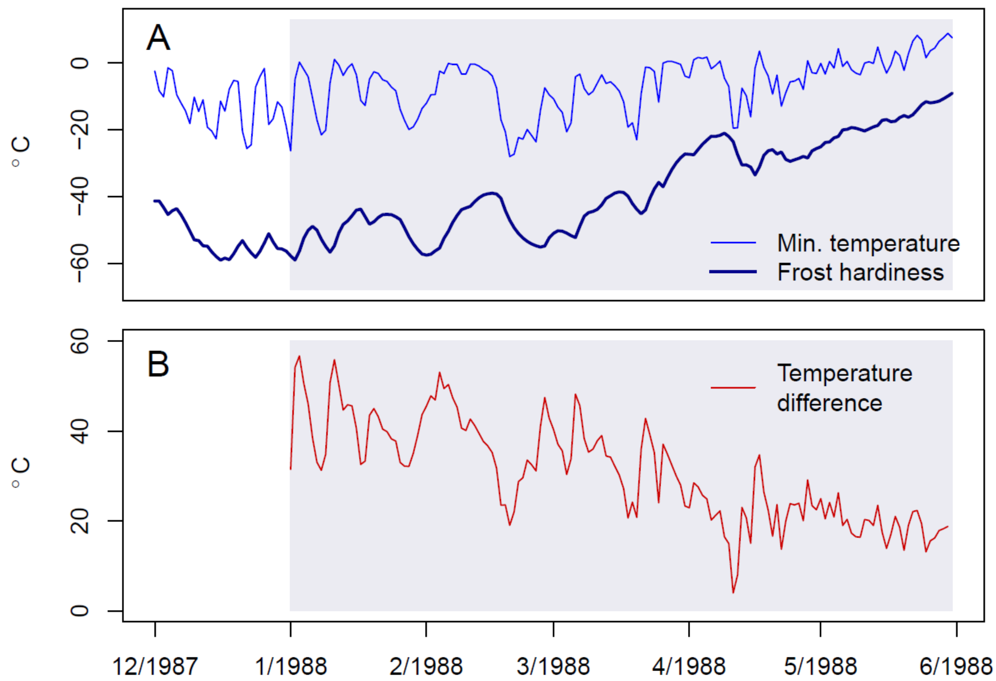

Fig. 3 Daily minimum temperature and modelled frost hardiness level (A) and the difference between frost hardiness level and minimum temperature (B) in December 1987 to May 1988 at Jyväskylä weather station. Year 1988 was classified as an extreme year for REL_TMIN variable in Jyväskylä, due to low value of REL_TMIN (lowest difference in modelled frost hardiness and minimum temperature in April). Only the time period from January to May (gray box) was used for finding the REL_TMIN variable, but frost hardiness was also calculated for previous year December to find a suitable initial value for the beginning of January.

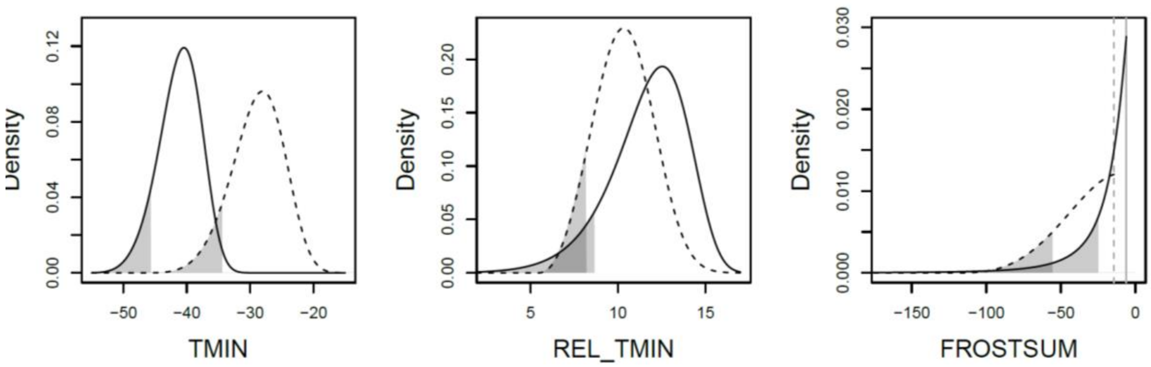

Fig. 4 Examples of density functions of the GEV distributions for minimum winter temperature (TMIN), minimum temperature in relation to modelled frost hardiness (REL_TMIN) and the frost sum of snowless days (FROSTSUM). For TMIN and REL_TMIN the GEVs of Karasjok (solid line) and Heinola (dashed line) weather stations are presented. For FROSTSUM, example sites from northern Finland (solid line, negative shape parameter) and southern Finland (dashed line, negative shape parameter) are presented. The shaded areas demonstrate the values below the 10-year return level. The vertical lines in the FROSTSUM subplot represent the thresholds used in fitting the "peaks over threshold" distributions. Note that sub-figures have different ranges of y-axis.

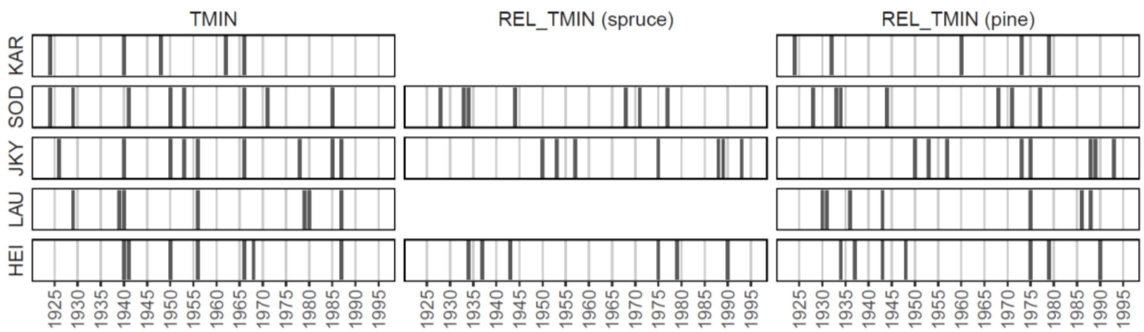

Fig. 5 Years classified as extreme years (dark vertical bars) in the TMIN (minimum winter temperature) and REL_TMIN (minimum temperature in relation to modelled frost hardiness) variables at each weather station. Names and locations of weather stations are shown in Fig. 1. Extreme years in REL_TMIN (spruce) are not shown for stations Karasjok (KAR) and Laukansaari (LAU), as they were not used for any spruce sites (no spruce sites close to them, see Fig. 1).

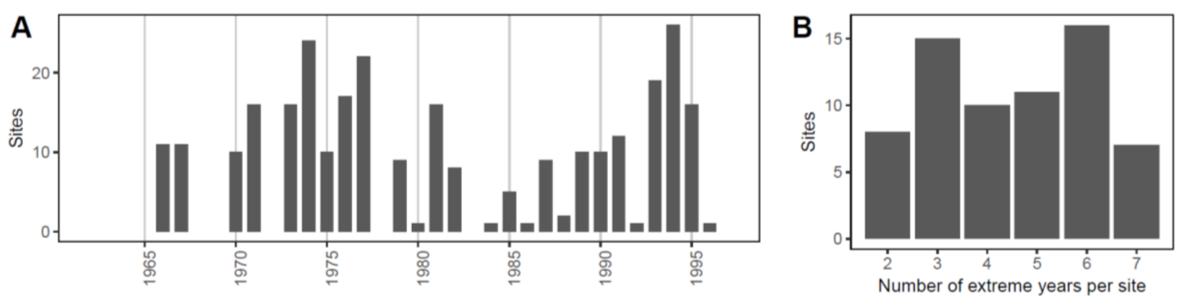

Fig. 6 Number of sites in each year where FROSTSUM (i.e., the frost sum of snowless days) variable was classified as extreme (A), and the distribution of total number of extreme years per site (B). The FROSTSUM variable was derived from the gridded weather data for each site separately

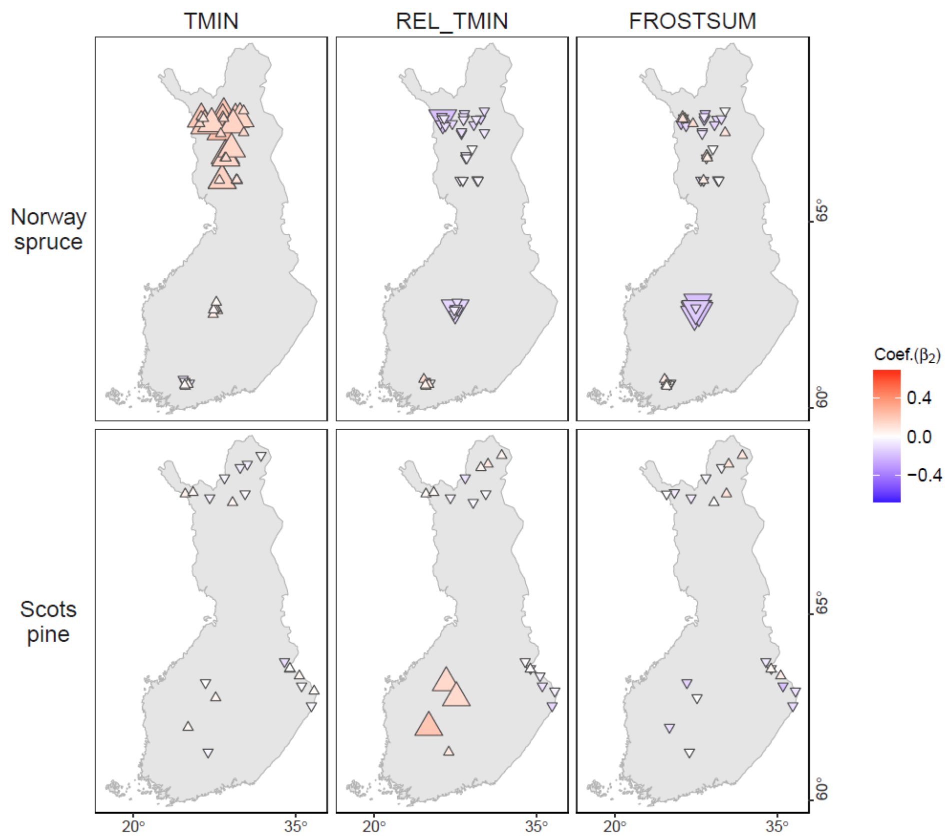

Fig. 7 Coefficients and statistical significance of the frost variables in the dummy model (Eq. 1). Small symbols represent statistically non-significant and large symbols significant coefficients ($p < 0.05$). The down-facing triangles represent negative and up-facing triangles positive coefficients. Note that some random variation has been added to the site coordinates so that symbols of nearby sites would not cover each other. See the exact locations of sites in Fig. 1. The non-significant symbols are always drawn on top of the significant ones

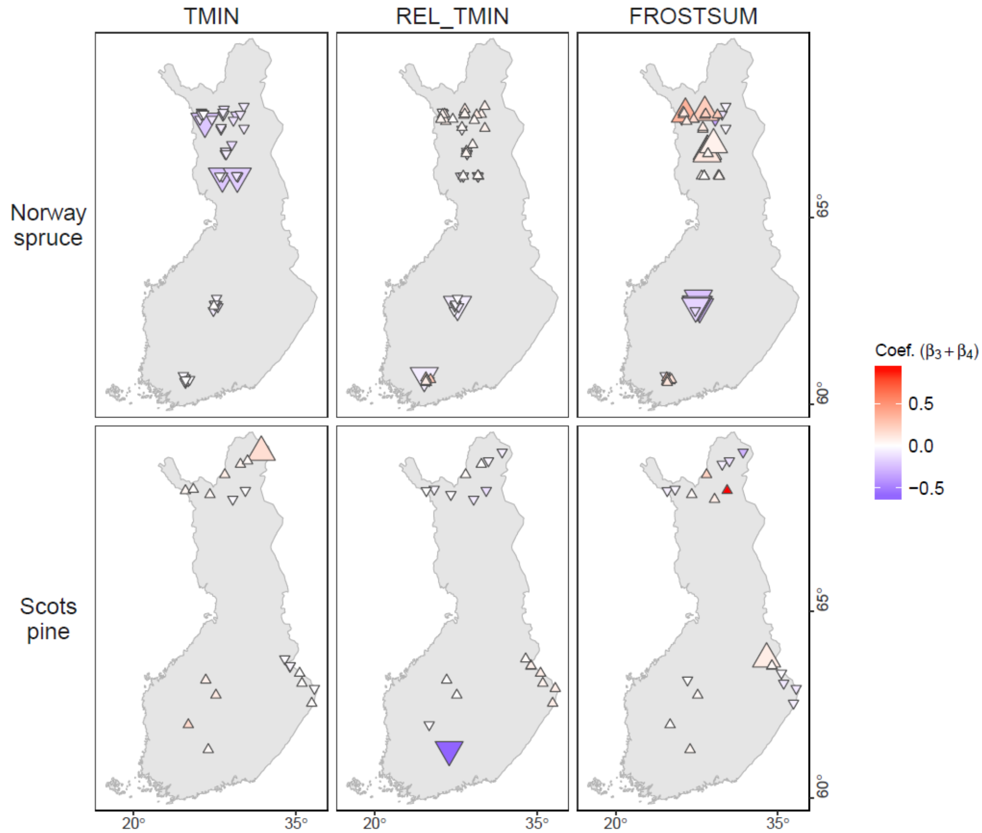

Fig. 8 Results for the "slope model" (Eq. 2): Coefficients for the slope of the frost variables during extreme years. The size of the symbol describes whether the slope model was significantly improved compared with the dummy model ($p < 0.05$, likelihood ratio test results). The down-facing triangles represent negative and up-facing triangles positive coefficients. Note that some random variation has been added to the site coordinates so that symbols of nearby sites would not cover each other. See the exact locations of sites in Fig. 1

Tables

Table 1. Descriptions of frost variables and their range in the whole study area.

	Description	Covered time window	Source data	Years included	Range (whole study area)
TMIN	Lowest daily minimum temperature	Previous July to growth year June	Weather stations	1922 to 1997 (excl. 1927, 1945)	-50 to -21.5
REL_TMIN	The smallest difference between modelled daily frost hardiness and daily minimum temperature	Growth year January to May	Weather stations	1922 to 1997 (excl. 1927, 1945)	3.1 to 16.9
FROSTSUM	Sum of temperatures below 0°C during days with no snow cover	Previous July to growth year June	FMI grid	1962 to 1997	-216.3 to 0

Electronic supplementary materials

Supplementary material 1.

Table S1.1 Details about the tree-ring sites, name and distance of weather stations for each site, the model coefficients for frost variables in dummy and slope models, and the 10-year return level for FROSTSUM variable in each site (return levels for other two frost variables were defined for weather stations and can be found below this table).

Table S1.2 10-year return levels for TMIN and REL_TMIN variables for the weather stations. Although REL_TMIN differed slightly for spruce and pine (different parametrization of frost hardiness model) the return levels were the same.

Figure S1.1 Scatterplots of p-values for frost variable coefficients (dummy models) against distance between plot and the nearest weather station.

Supplementary material 2. Detailed description of the frost hardiness model and the modifications made to it in this study