BRIEF REPORT

Climatic Determinants of Introduced Sitka Spruce in Hiiumaa Island, Estonia

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Abstract

Tree-ring records of Sitka spruce growing in Hiiumaa (Estonia) were investigated to illustrate their growth variability and its climatic determinants. A chronology comprising ring-width series of eight individuals from the Suuremõisa forest park was correlated with local climatic records. The growth variability of this species introduced to Hiiumaa was statistically explained profoundly by winter temperature and early-spring precipitation. Comparisons were also made with local tree-ring data of Norway spruce. Both the native and non-native species responded positively to precipitation in June and negatively to precipitation in April. The growth of Sitka spruce in Hiiumaa may actually be less tolerant to winter temperatures. Common to Sitka spruce results from Hiiumaa, tree-ring data representing conspecific native populations from north-west North American sites indicated positive responses to mid-winter temperatures. Based on these results, low winter temperatures and early-summer droughts may both threaten the survival of the individuals of this species in Hiiumaa.

Keywords: *Picea sitchensis*, introduced tree species, climate relationships, Hiiumaa

Introduction

A group of big Sitka spruces (*Picea sitchensis* (Bong.) Carr.) is growing in the Suuremõisa forest park in Hiiumaa Island, Estonia. This North American tree species was first introduced to Estonia more than one hundred years ago (Klinge 1883, Laas 1987). However, nearly all of the following cultivation attempts of Sitka spruce in Estonia have failed. Several studies reported the planted trees to have perished from cold winter conditions (Berg 1924, Haller 1929, Kasesalu 2012, Kasesalu et al. 2018). At present, the Suuremõisa group of Sitka spruces represents the only full-grown locality of the species in Estonia. In 1976, there were seventeen viable Sitka spruces growing in the park (Tamm and Ratas 1976).

We hypothesize that dendrochronologically produced tree-ring data of these trees may be used for investigating their climate-growth relationships and to reveal the particular climate-growth relationships that may have impaired the success of Sitka spruce and eventually led to failure of several cultivation trials in Estonia. In so doing, this paper has multiple aims. First, the tree-ring chronology of Sitka spruce is produced for the Suuremõisa forest park, Hiiumaa Island, to portray the radial growth variability of this tree species in Estonia. Second, the tree-ring data is compared to local climatic records to demonstrate the climatic determinants of the species in these site conditions. Third, the climatic correlations of Sitka spruce are compared to similar associations of Norway spruce. This analysis is carried out using a Norway spruce tree-ring chronology recently constructed for a Hiiumaa site (Helama et al. 2018) which, however, remains hitherto unanalysed for its local climatic response. Previously, there have been similar interspecific analyses conducted in Poland (Feliksik and Wilczyński 2008, 2009), and a comparison was made between their and our findings. Fourth, the climatic determinants of non-native Sitka spruce in Hiiumaa are compared to similar associations of conspecific native populations from north-west North American sites. This analysis is made possible by the tree-ring data from the International Tree-Ring Data Base (Grissino-Mayer and Fritts 1997, Zhao et al. 2019). Collectively, the main aim of this paper is to demonstrate the sensitivity of this exotic (non-native) tree species to climatic variations using the Sitka spruce tree-ring data from western Estonia in comparison to climate sensitivity as indicated for native spruce populations from western Estonia and north-west North America.

Material and Methods

Fieldwork and age estimates

Nine trees out of thirteen big Sitka spruces were cored in Suuremõisa forest park (Figure 1). The trees were cored from the north side of each trunk at 1 m stem height, using a 60-cm increment borer. As the girth of the thickest tree was 317 cm (radius approx. 50 cm), the borer bit should reach to the pith of the trunk of all trees. In fact, most of the cores passed the pith in a few centimetres (when the eccentricity of the trunks made it difficult to estimate the cross-sectional centre), while two cores exactly hit the pith. The biggest number of tree rings counted was 113. First, these estimates confirmed the century-long age of the Suuremõisa Sitka spruces. Second, the tree-ring samples offered an opportunity to compare their radial growth series with those of temperature and precipitation records.

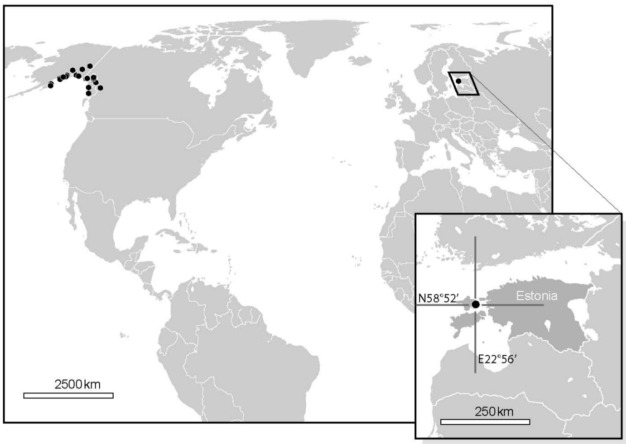

Figure 1. Maps showing Hiiumaa Island in Estonia (dark grey with a dot) and the north-west North American Sitka spruce sites (black dots)

Tree-ring analyses

Tree-ring widths were measured to the nearest 0.01 mm by using a Leica S4E stereomicroscope and a Lintab digital positioning table (Rinntech). First, the tree-ring widths of the nine Sitka spruces were compared with each other visually to cross-date the resulting series. As one of the ring-width series was found to notably deviate from the growth patterns of the other studied trees, the data of this particular tree was rejected from any further analyses. Judging by its tree-ring widths, showing long-term growth depressions over extended intervals of time, this sample was originating from an individual suppressed under the dominant trees (Figure 2a). Using the approach of Läänelaid et al. (2008), the tree-ring series were plotted as cumulative growth graphs. This approach showed that the particular tree was notably thinner than others (Figure 2b). Second, the tree-ring series were used to produce mean tree-ring width chronologies. These were computed by the Arstan software (Cook 1985). In so doing, the negative exponential function or regression line was first fitted to each tree-ring series. A set of tree-ring index series was derived as ratios between the observed tree-ring values and those of the detrending curve. Next, the cubic smoothing spline with rigidity of 128 years was fitted to

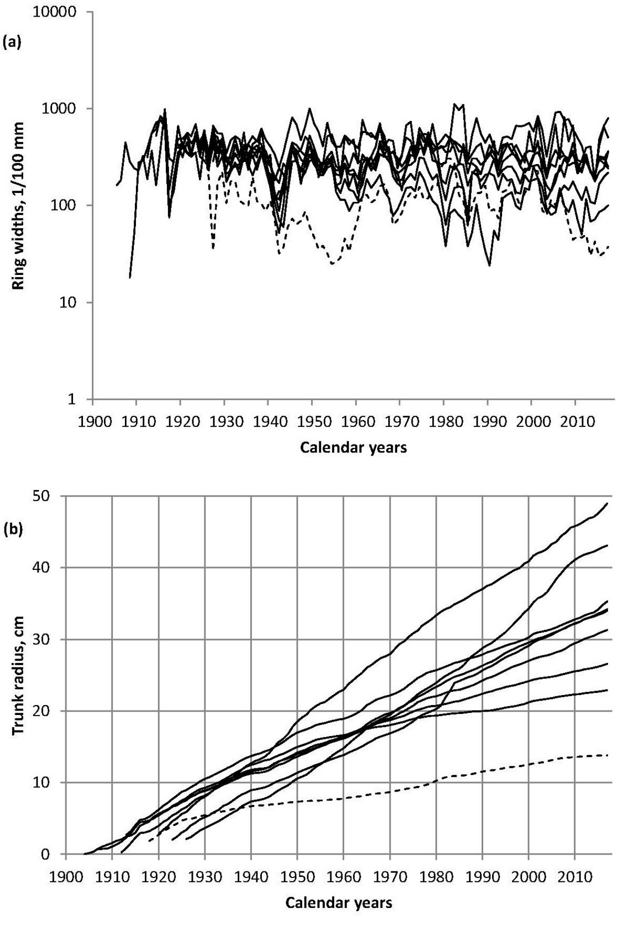

Figure 2. Ring-width series of nine Sitka spruces growing in the Suuremõisa forest park (a). The tree No. 4 (dashed line) appears to exhibit growth variations that deviate from the growth of other trees. Radius growth as recorded in the nine tree-ring width series of Sitka spruces (b). Dashed curve indicates the tree No. 4 (see text for discussion)

the index series resulting from the first detrending and a second set of tree-ring indices was derived as ratios between the indices from the first detrending and the spline curve fitted to such series. Thereafter, the resulting series of tree-ring indices were pre-whitened to remove the autocorrelation present in the series (Cook 1985). Finally, the series of tree-ring indices were averaged into their respective mean chronologies.

Norway spruce tree-ring data

It may be illustrative to compare the climate-growth relationships of the non-native Sitka spruces results from analyses of native Norway spruces (*Picea abies*) growing in a nearby site. For such purpose, tree-ring data from Kärdla, located also in Hiiumaa Island, was employed. This data was recently published as a part of larger dataset of Norway spruce tree-ring chronologies used for the analyses of past climate variability in western Estonia (Helama et al. 2018). Here, a set of tree-ring width series of twelve Norway spruces was used to calculate a mean chronology using the same detrending methods applied to Sitka spruce data. We applied similar climate correlation analyses as for Sitka spruce to the resulting Norway spruce chronology.

Native Sitka spruce tree-ring data

While Sitka spruce is non-native to Estonia (and Europe), tree-ring data from its native environment is available from the International Tree-Ring Data Bank (ITRDB) (Grissino-Mayer and Fritts 1997, Zhao et al. 2019). The data consists of 32 Alaskan and six Canadian tree-ring chronologies (Figure 1). Their climatic determinants were estimated using the Dendrobox software (Zang 2015) that explores and accesses the tree-ring data from the ITRDB via web interface available at *URL*: http://dendrobox.org. The tree-ring series are detrended using methods similar to our spline detrending (*see* Zang 2015).

Results

Climatic determinants

Several climatic records were considered for the climate-growth analyses, all of which originate from meteorological stations in Hiiumaa Island. Unfortunately, none of them provide continuous century-long records of both temperature and precipitation. For correlation analysis the most reasonable data seemed to be the monthly temperature records observed in Ristna. This meteorological station is located approx. 50 km west of Suuremõisa, and provides temperature data for the period 1946-2017. Monthly precipitation sums from Kärdla station were available for the period 1886-2008. This station is located approx. 15 km north-west of Suuremõisa. Correlations of tree-ring width chronologies with monthly air temperatures and precipitation amounts were calculated using the DendroClim software (Biondi 1997, Biondi and Waikul 2004). Correlations were determined over the 1947-2008 period covered by both the temperature and precipitation records. The mean chronology computed from pre-whitened index series (i.e. residual chronology) was used for climatic analyses. The correlations showed that the growth of these trees was predominantly related to winter and early spring temperatures (Figure 3a). We found statistically significant and positive correlations with monthly mean temperatures over this season from December (prior to the year of growth) through April (concurrent year), with exception of March. Among the summer months, the only relationships indicated by statistically significant correlation was that of the negative correlation to August temperature.

Correlations with precipitation variables did not show similarly strong positive relationships (Figure 3b). Moreover, the precipitation relationships with statistical significance were not concentrated on winter months.

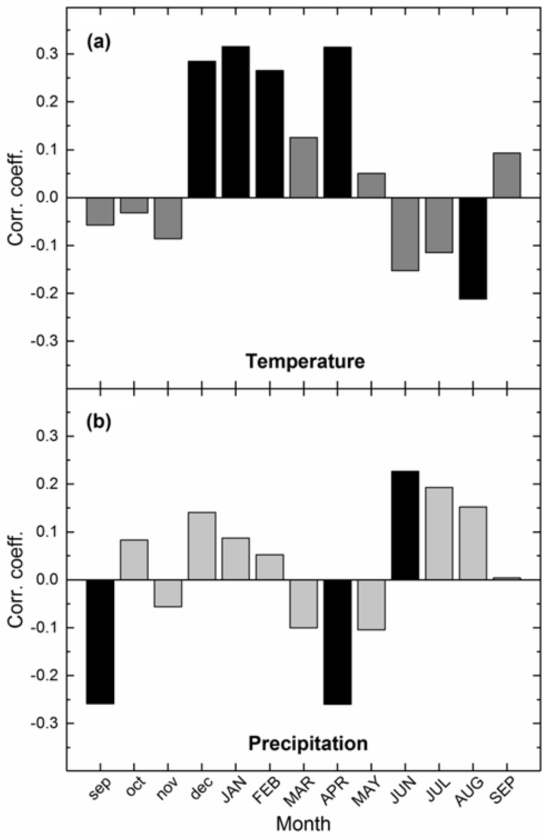

Figure 3. Bootstrapped correlations showing the relationships between Sitka spruce tree rings and monthly mean temperatures (a) and precipitation sums (b). Tree-ring widths were compared (1947-2008) separately to weather variables of the previous (small letters) and concurrent year (capital letters). Statistically significant relationships (0.05 level) are indicated as filled histograms

By contrast, the precipitation correlations identified negative associations with the rainfall in September of previous year (with average temperature +12.7 °C) and with that of April of current year (with average temperature +3.2 °C). Among these variables, the effect of June precipitation was the only positive, statistically significant association found for Sitka spruce.

Comparison with Norway spruce

In comparison to Sitka spruce, it seemed that monthly temperatures had no such dominating effect on the growth of Norway spruce in Hiiumaa Island. That is, there were no statistically significant correlations between the growth variability and temperature variables for that species (Figure 4). Clearly, these results indicate that while the non-native Sitka spruce may be markedly sensitive to winter temperatures, the Norway spruces native to Hiiumaa is not markedly related to monthly temperatures in any of the studied months.

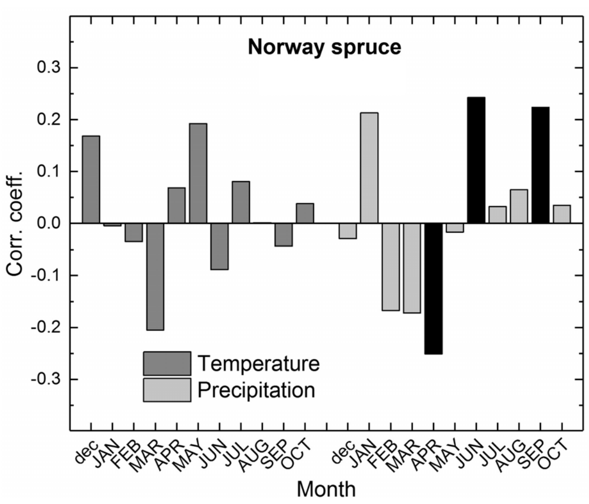

Figure 4. Bootstrapped correlations showing the relationships between Norway spruce tree rings and monthly mean temperatures and precipitation sums. Tree-ring widths were compared (1947-2008) separately to weather variables of the previous (small letters) and concurrent year (capital letters). Statistically significant relationships (0.05 level) are indicated as filled histograms

Instead, the precipitation variables of some months were indeed found to correlate significantly and positively with Norway spruce tree-ring data. More specifically, the strongest positive correlations with precipitation variables were identified for June and September (Figure 4). Notably, the statistically significant positive correlations between the Sitka spruce growth and winter/early spring temperatures were accompanied by the significant and positive correlations with growing season precipitation, of which the early summer precipitation signal appeared common to both spruce species. Apart from these positive associations, however, it appeared that there is a negative correlation evident between the Norway spruce tree-ring data and precipitation in April. Moreover, this association mimicked the negative correlation with April precipitation we found for Sitka spruce (Figure 3b).

Moreover, the correlations (1928-2016) between the Sitka spruce tree-ring series averaged 0.42, whereas those of Norway spruce showed a mean correlation of 0.29. Over the same period, the correlation between the two mean chronologies was 0.25.

Collectively, these findings indicate that the growth variations of the native and non-native spruce species were not due only to dissimilar climatic factors but could be explained by their positive response to early summer precipitation and negative response to early spring precipitation, common to both species.

Comparison with North American Sitka spruce

Tree-ring chronologies representing the growth of Sitka spruce in its native north-west North American environments were explored for their climatic determinants (Figure 5). The responses were overall positive for

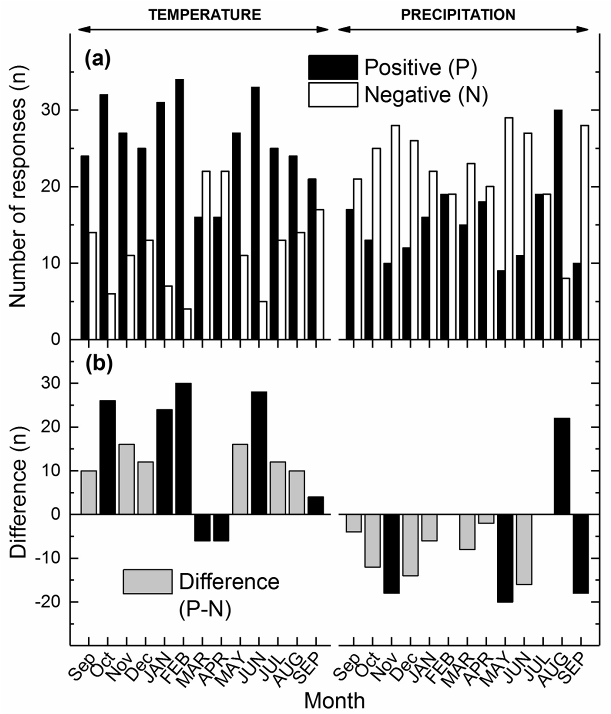

Figure 5. Numbers of positive and negative relationships between Sitka spruce tree rings and monthly mean temperatures and precipitation sums (a) and the difference between the number of positive and negative relationships (b) in 38 Alaskan and Canadian sites. Statistically significant relationships (0.05 level) are indicated for the differences as filled histograms

temperature and negative for precipitation variables. Common to Sitka spruce in Hiiumaa, the temperature responses of native Sitka spruce were positive over the mid-winter months (January-February). In contrast to Hiiumaa responses, the North American data showed a concentration of negative responses to precipitation in spring/early summer (May-June).

Discussion and Conclusions

The climate-growth relationships of the native Sitka spruces in North America are computed using the bootstrapped response function to obtain response coefficients (Guiot 1991), similarly to our analyses of non-native Estonian Sitka spruce data. These analyses make use of interpolated climate data from the four nearest 0.5-degree grid cells of the CRU TS3.21 climate data of monthly temperature and precipitation records (Mitchell and Jones 2005). Over these Alaskan and Canadian sites, the mean temperatures of January and June, representing the coldest and warmest months, were -7.4 °C and +11.9 °C, respectively. The months with the highest and lowest precipitation were October and June, with mean precipitation value of 229 mm and 91 mm, respectively. These values were obtained as estimates generated by the Dendrobox software. Here, the numbers of positive and negative responses to monthly mean temperature and precipitation sums were counted for the thirty-eight sites and the difference between their numbers calculated to estimate a common climate signal among the sites, i.e. whether any of the monthly coefficients were dominated by either positive or negative indications. Bootstrapping was applied to test the significance of this tendency by resampling (n = 10,000) the coefficients and calculating the differences between the numbers of positive and negative (surrogate) responses. This testing was done separately for temperature and precipitation correlation coefficients.

Our findings indicate that the growth variability of Sitka spruce was sensitive to temperature variations during the winter through early spring season. This association concurs with several previous observations suggesting that the introduced Sitka spruce suffers from cold winter conditions in the same region (Berg 1924, Haller 1929, Kasesalu 2012, Kasesalu et al. 2018). Similar connections were not evident here for Norway spruce, which reinforces the previous findings in Poland showing that Norway spruce was more resistant to low temperatures than Sitka spruce (Feliksik and Wilczyński 2009). By contrast, the cold season temperature was recently found as the decisive factor limiting Scots pine growth variability in the same region, to an extent to allow this variable to be reconstructed from a northern Poland ring-width chronology (Balanzategui et al. 2018). Recent tree-ring analyses have indicated similar results for Norway spruce in the Estonian mainland with significant correlations between the regional mean chronology of spruce and temperatures in December (prior to the year of growth) and January (Läänelaid and Eckstein 2012), and especially for sites located in the eastern part of the country (Helama et al. 2016). Continentality of climate is increasing from the west to the east over this region (Jaagus et al. 2003) tending to bring lower winter temperatures more frequently in the east. This gradient may explain, at least partly, also the differences in the growth responses and could suggest that Sitka spruce is to survive more likely under milder winter climate.

In western Estonia, the growth response of Norway spruce, indicating sensitivity particularly to early-summer (June) droughts, demonstrated here for our Hiiumaa site, was similar to that observed for the mean chronology of Estonian mainland (Läänelaid and Eckstein 2012, Läänelaid et al. 2015), several individual sites across western Estonia (Helama et al. 2016), and for their mean chronology over the same (Helama et al. 2018). The same response to June precipitation was observed here for Sitka spruce, this variable thus representing a common climatic factor behind the growth variability of both spruce species. These results mimicked the tree-ring findings from Poland where both the Sitka spruce and Norway spruce showed similar positive association with June precipitation (Feliksik and Wilczyński 2009). Clearly, both the native and non-native spruce species remain notably susceptible to early summer moisture conditions. Moreover, this factor may represent another threat to survival of Sitka spruce, in addition to cold winter temperatures. In fact, the increased damage and mortality of Norway spruce was previously reported in southern Finland and connected to drought in well-drained sites (Mäkinen et al. 2001). This response was, on the other hand, the most notable deviation between the native and non-native Sitka spruce climate-growth associations, the north-west North American data indicating negative responses to precipitation in May and June. Over these months, the precipitation was estimated to total 190 mm in these North American tree-ring sites (the values derived from Zang 2015), greatly exceeding the mean amount of May-June precipitation, 75 mm, observed in Kärdla meteorological station.

It is noteworthy, in any case, that the drought-tolerance of at least Norway spruce may be modified by site and soil conditions. In particular, it has been indicated that spruce trees with more growing space show reduced susceptibility to drought (Kohler et al. 2010), that spruce trees growing on a shallow, well-drained soil showing poorer growth are more sensitive to drought than the trees of the same species growing on deep, silty soils (Rehschuh et al. 2017), and that spruce trees growing on xeric site conditions are more vulnerable to soil water deficits that those at the mesic site conditions where they remained vulnerable to water deficits a shorter duration compared to trees at the xeric site conditions (Lévesque et al. 2013). It appears that the particular factor, the drought-tolerance, may actually represent a climatic determinant that is markedly depending on the conditions at the growing site, with a degree of spatial variability.

Additionally, the climatic correlations, albeit not all reaching statistical significance, suggested that the growth of Sitka spruce may show a pattern of climatic response whereby it is controlled predominantly positively by precipitation and negatively by temperature variations, during the three summer months. Possibly, this may indicate that integrating the two types of data, temperature and precipitation, into an integrated variable, such as the climatic water balance (Thornthwaite 1948) or the standardized precipitation evapotranspiration index (Beguería et al. 2014), may help to obtain even a higher dendroclimatic correlation than those observed here separately for temperature and precipitation. Such a pattern of climatic response was not, however, observed for Norway spruce for which all monthly temperature correlations remained statistically non-significant. From this, it follows that no meaningful interspecific comparison using the derived climatic indices (Thornthwaite 1948, Beguería et al. 2014) could likely be carried out.

Another common factor behind the climatic determinants of both spruce species in Hiiumaa was that represented by negative correlation to precipitation in April. Similar correlation was found previously for Sitka spruce in Pomerania in Poland (Feliksik and Wilczyński 2008). In that study, the potential reasons for this connection were not discussed. The negative correlation indicates that Sitka spruce may not suffer from winter desiccation which effects could then be released by spring moisture surplus. Hypothetically, this correlation could result from increased overcast conditions that may inhibit the start of the photosynthesis in the early part of the growing season or from freezing injury the excess of soil moisture could cause if the season undergoes sub-zero temperature events that may also relate to reduced nutrient uptake. Further studies are needed to evaluate these and other factors.

Overall, the climatic determinants of Sitka spruce were rather consistent in the Hiiumaa site with those presented previously for the Sławno Forest District in Pomerania, where the tree-ring data of this species correlated highly positively with temperatures during the winter and spring months (January through April) and negatively with precipitation during the summer season (June through August) (Feliksik and Wilczyński 2008). The responses were found also to differ; however, as the Hiiumaa Sitka spruce tree rings did not correlate distinctly with November (prior to the year of growth) and May temperatures, as they did in Poland. It is notable that even more deviating results were evident for more distant sites. That is, relationships neither with winter/early spring temperatures nor with spring/summer moisture regime were evident for planted Sitka spruce in Scotland, where climate-growth correlations were rather weak and negative for temperatures in June and September and for precipitation in February and October (Dengel et al. 2009). It is possible that this dissimilarity of climatic connections has resulted from a relatively young age of the studied trees in Scotland (planted in 1953) or, possibly, the relationships deviate simply due to types of climates constraining the tree growth reactions differently in Scotland and in the Baltics. Scotland is milder in winter; wherefore winter temperatures may not be limiting there. Moreover, several other tree individuals than those studied here have likely perished over the past century at least partly because of climate conditions. In other words, the results shown here are likely not to represent a random sample but trees having adapted best to prevailing conditions. This may have caused additional alteration of climate-growth relationships in comparison to trees without similar constraints.

Acknowledgements

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