METEOROLOGICAL SENSITIVITY OF TREE-RING WIDTH OF SCOTS PINE AND NORWAY SPRUCE IN DRAINED STAND

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Abstract. Tree growth in drained peatland forests is influenced by complex interactions between species specific traits and climatic variability, yet these relationships remain insufficiently understood. This study examined the sensitivity of Scots pine (Pinus sylvestris) and Norway spruce (Picea abies) to temperature, precipitation, and the standardized precipitation-evapotranspiration index (SPEI) using tree-ring data and bootstrapped correlation analysis. Climate-growth relationships were analysed for two periods: early (1917-1970) and later (1971-2022). Climate growth responses of pine and spruce showed similar sensitivity to spring temperatures in the early period, but diverged in their responses to temperature and moisture conditions during the later period. Pine exhibited a consistent positive response to late winter and early spring temperatures (February–April). In contrast, the response of spruce to March-April temperatures was non-stationary, reflecting increased drought sensitivity in the later period. During the early period, both species exhibited negative carry-over effects from excessive dormant-season (November) moisture regime, with spruce showing an extended negative response to elevated SPEI values from October to December. No clear evidence of summer drought induced growth reduction was observed in spruce, suggesting that local hydrological conditions in drained peat soils may buffer drought effects. However, a negative correlation with August precipitation in later stand development for spruce indicated insufficient soil aeration, likely due to natural drainage deterioration and thinning induced reductions in evapotranspiration. These findings underline that Scots pine maintains greater climatic stability under long-term drainage, whereas spruce requires careful management of drainage regimes to ensure sustained growth and resilience. This study highlights the need for species- and site-specific strategies to enhance forest resilience under a changing climate.

Keywords: Scots pine, Norway spruce, weather-sensitivity, drained soils, organic soils.

Introduction

Climate change is leading to warmer and drier conditions, with increased climate variability and more frequent extreme weather events [1]. In Europe, these changes are expected to cause vegetation zone shift northward [2; 3]. While droughts in southern and central Europe may severely limit conifer species growth [4; 5], the northern regions could experience more favourable growing conditions due to milder winters and earlier springs [6]. However, these benefits pose risks, such as increased susceptibility to spring frosts that can damage early-budding trees [4; 7; 8]. Therefore, adaptive management is essential for sustainable forestry, by selecting planting materials suited to future climatic conditions [9-11].

Tree-ring width (TRW) is commonly used proxy to evaluate the impact of past environmental conditions on tree increment [12-14]. Analysing TRW helps assess a tree's sensitivity to historical weather patterns. Meteorological sensitivity of tree-ring width refers to the phenomenon where climatic factors such as temperature, precipitation, and drought influence the formation and variation in the annual growth rings of trees. Meteorological sensitivity of tree can be non-stationary [15], meaning it varies over time, with climatic factors like temperature and precipitation exerting differing influences across periods [16]. Additionally, climate impacts on tree growth often exhibit carry over effects, where past climatic conditions influence growth in subsequent years due to poorly stored carbohydrate reserves, root damage, or delayed physiological adjustments [17]. Variability of meteorological sensitivity is driven by changing climate patterns [18], shifts in tree physiology with age [19,20], and disturbance events [18; 21], all of which alter resource availability and growth responses. Consequently, trees may exhibit strong meteorological sensitivity in certain periods while showing diminished or altered responses in others [15]. Understanding tree species sensitivity is vital for predicting how tree species will cope with future climate [22].

Generalizing species climate-responses across different climatic gradients is challenging [22]. Even within the same region, growth responses can vary [15; 23; 24], influenced by local site conditions, e.g. soil properties [25; 26], microclimate [27], and management practices [28]. Peat sites in particular have distinct hydraulic properties [29], and have been extensively drained for forestry [30]. Drained peat (organic) soils exhibit altered hydrological properties [31]. Trees growing on drained peat soils often experience altered hydrological conditions with both deficits and excesses impacting growth. During dry periods root system may not access sufficient moisture making trees more susceptible to drought [31], whereas during wet periods, excessive soil water can remain in peat for extended periods, particularly in case of poor drainage system condition [32], thereby reducing increment formation [33].

Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) are the two most common coniferous tree species in Latvia, with high ecological and economical value. Recent studies have raised concerns about the future resilience of species distributions in response to climate change [2; 4; 5]. Warmer winters can extend the growing season for Scots pine, potentially enhancing annual growth [6; 28], however, increased drought sensitivity poses management challenges [4; 6]. Norway spruce is particularly susceptible to water availability [5; 34], both excessive and limited [15] moisture regime can constrain spruce growth. Understanding the growth responses of local conifer species to future climate conditions is particularly important in drained sites, where water availability can fluctuate significantly. Therefore, the aim of the study was to asses Norway spruce and Scots pine tree ring width weather sensitivity growing in drained peat soils. Evaluating the meteorological sensitivity of trees across different soil conditions is essential for prioritizing species selection in regeneration plans. Determining the future growth potential of common conifer species in drained peat soils is crucial for adaptive management and sustainable forestry.

Materials and methods

Study site, sampling and measurements

The studied forest stand is located in Latvia (24.13°E, 56.76°N) on a former transitional mire, drained through an open ditch network at the end of the 19th century. According to local typology the site is classified as *Myrtillosa mel*. [35], dominated by Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). The soil consists of a peat layer more than 80 cm in thickness, overlaying the mineral material bedrock. The area features flat topography and lowland conditions (elevation < 15 m a.s.l.).

The climate at the site can be described as mild. During the period of 1985-2015 the mean annual temperature in this area was + 7.0 ± 0.91 °C. In this time period the warmest and coldest months were July and January with mean temperatures of + 18.1 ± 1.6 °C and -3.5 ± 3.5 °C, respectively. Annual precipitation was 667.2 mm·yr^{-1}, with the highest and lowest mean precipitation in July (81 ± 33.7) and March (36.5 ± 15.0 mm), respectively.

The study site, with the area of 0.25 ha, has been a long-term research object, with periodic surveys of stand characteristics (Table 1). According to the most recent stand inventory, conducted in 2022, the stand was dominated by 125-year-old Scots pine and 100-year-old Norway spruce trees. Stand thinning was carried out 2020, and was evident by the reduced basal area (Table 1).

Table 1

Stand characteristics across inventory years (1951-2022) with respective stand species structure and mean values of stand DBH, height, basal area and standing stock

Year	Stand structure	DBH, cm	H, m	Basal area, m^2·ha^{-1}	Standing stock, m^3·ha^{-1}
1951	6P$_{50}$ 4E$_{30}$	19	21.5	28	287
1957	6P$_{55}$ 5E$_{55}$	20.5	22.5	30	342
1966	6E$_{45}$ 4P$_{65}$	23.5	25	33	398
1980	6E$_{60}$ 4P$_{80}$	26	27.5	38	500
1991	6E$_{70}$ 4P$_{90}$	28	28.5	44	584
1995	6E$_{75}$ 4P$_{95}$	30	30.5	46	624
2005	6E$_{85}$ 4P$_{105}$	32	32	44	633
2011	6E$_{90}$ 4P$_{115}$	33.6	33.3	42	631
2022	6P$_{125}$ 4E$_{100}$	35.5	34.2	17	258

Forest stand inventory and sample collection were conducted in the summer of 2022. A single increment core was extracted from each living tree using a Pressler’s increment borer. In total, 44 samples were collected, dried, and mounted on wooden supports. Tree-ring width was measured with an accuracy of 0.01 mm using a LINTAB6 measuring system (RinnTech, Heidelberg, Germany).

Data analysis

Tree ring width (TRW) time series were cross dated using COFECHA program [36] to ensure that each tree ring is assigned with a correct year. Age related trend and other non-climatic influences on growth were removed by detrending TRW series using a cubic smoothing spline with 70-year rigidity parameter (dplR package) [37]. Visual assessment of detrended TRW time series were performed to ensure that the detrending process effectively removed unwanted trends without distorting the data. Descriptive statistics for TRW time series were calculated using the rwl.stats function (dplR package) providing first order autocorrelation (ar1) and Gini coefficient. An autoregressive detrending approach (detrend, method = ”Ar”) was applied, eliminating first-order autocorrelation from the series. A principal component analysis (PCA) was performed on the detrended TRW series for the period 1980-2015 to scrutinize common growth patterns of studied species.

Mean monthly temperature, precipitation sum, and the standardized precipitation-evapotranspiration index (SPEI) - a proxy for water availability [38] – were obtained from the Climatic Research Unit of the University of East Anglia . Dataset was filtered to retain only records from the location closest to the study site (24.13°E, 56.76°N). Monthly climate variables were organized into a time window extending from June of the previous year (previous June) to October of the current growth year, to account for potential lag effects on tree growth. Climate–growth relationships were assessed by correlating standardized tree-ring chronologies with these climate variables over the full period (1917-2022) and two subperiods (1917-1970 and 1970-2022). To obtain robust estimates and account for non-normality and autocorrelation, correlations were computed using a bootstrapped Pearson correlation analysis with 10^4 iterations [39] and only trees with a sample depth greater than 10 were included in the analysis. Correlations were considered significant if their 95% confidence intervals excluded zero.

Results and discussion

TRW series of 44 trees were successfully cross-dated, and averaged time series of each species were constructed. Visual assessment confirms that frequency of weather induced climate signal reduces with aging of trees (Fig.1).

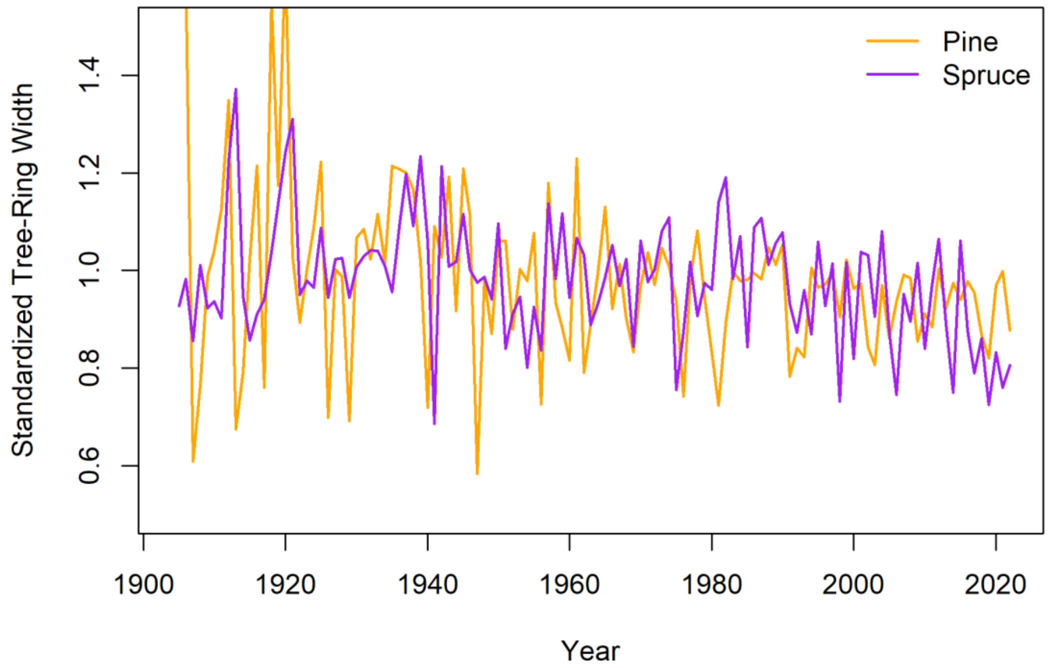

Fig. 1. **Standartized tree-ring width chronologies of trees growing in the drained stand**

Two principal components accounted for 31.7% of variance, 17.3% and 14.6%, respectively. PCA analysis of detrended TRW series showed differentiating between spruce and pine species (Fig. 2).

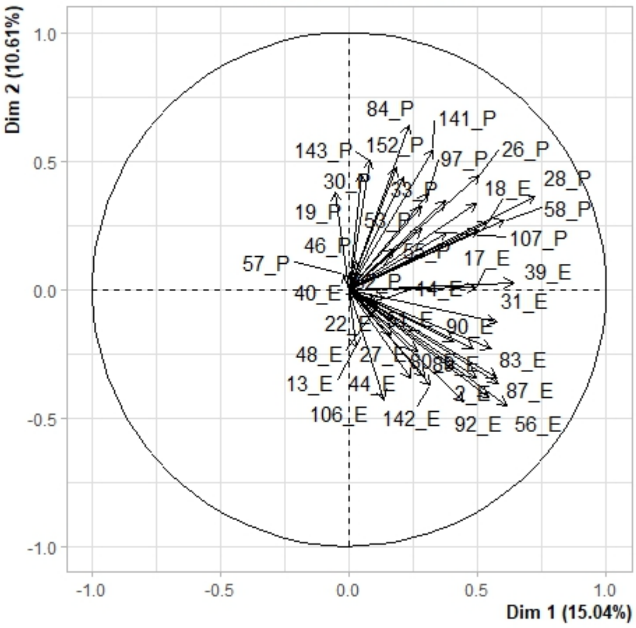

Fig. 2. **Principal component loadings of detrended TRW time series (P – Pine, E – Spruce)**

Both species showed non-stationary weather-growth responses, evidenced by a greater number of significant correlations with weather variables during the early period (spruce: 7, pine: 9) compared to the later period (spruce: 2, pine: 3) (Table 1.)

Table 2

Scots pine and Norway spruce climate-growth correlations for periods 1917-1970 and 1970-2022

Parameter	Spruce			Pine		
	1917-1970	1971-2022	1917-2022	1917-1970	1971-2022	1917-2022
Temp.Feb	0.24	0.12	0.2	**0.49***	**0.29***	**0.34***
Temp.Mar	**0.28***	0	0.14	**0.49***	**0.33***	**0.39***
Temp.Apr	**0.35***	-0.11	0.13	**0.31***	0.16	**0.22***
Prec.prev.Jul	0.19	0.08	0.13	**0.32***	0.2	**0.24***
Prec.prev.Sep	**-0.38***	-0.01	-0.17	-0.1	0.05	-0.05
Prec.prev.Nov	**-0.26***	0.25	0.01	-0.25	0.05	-0.08
Prec.Jan	0.2	-0.03	0.08	**0.27***	-0.1	0.05
Prec.Feb	-0.09	0.01	-0.02	0.21	**0.27***	**0.22***
Prec.Aug	-0.14	**-0.31***	**-0.25***	-0.1	0.01	-0.02
SPEI.prev.Oct	**-0.39***	0.07	-0.13	-0.15	-0.07	-0.11
SPEI.prev.Nov	**-0.51***	0.05	-0.19	**-0.25***	-0.08	-0.15
SPEI.prev.Dec	**-0.32***	0.14	-0.06	-0.18	-0.15	-0.16
SPEI.Jan	-0.09	**0.27***	0.1	-0.01	-0.13	-0.09
SPEI.Feb	0.05	0.1	0.1	**0.27***	-0.04	0.04
SPEI.Mar	0.24	-0.09	0.06	**0.41***	0.03	0.16

*significant bootstrapped Pearson correlations

During the early period (1917-1970), both species showed significant positive correlation with late winter and early spring temperatures [6,15,25,28,40]. Spruce displayed a non-stationary relationship with March-April temperature, while pine maintained a consistent positive correlation with February-April temperature throughout the common period (1917-2022), though with decreasing effect as trees age. Shift in the response of spruce to warmer spring temperatures confirmed that spruce was more drought sensitive compared to pine [4]. A likely explanation is the increasing water demand as trees age, making spruce more vulnerable to moisture limitations [15]. As a result, older spruce trees may experience pronounced drought stress during warmer springs. Additionally, due to the earlier onset of photosynthetic activity during warmer springs, spruce is more susceptible to frost damage, in case of a sudden temperature drop following a warm period [7; 8; 41].

Weather growth responses regarding water availability showed direct and carry over effects of weather conditions. During the early period, both species shared some similar responses to water availability in the dormant period (Oct-Dec), while differing responses were observed during the growing season (Jul-Aug). Both species showed significant negative correlation between TRW and SPEI in previous year November, suggesting that humid autumn conditions negatively affect conifer tree increment during early age, potentially due to excess moisture during the dormant period disrupting physiological processes. This effect was more pronounced in spruce than in pine [42], as indicated by additional significant negative correlations between TRW and precipitation in the previous year’s October and December. This can be attributed to higher physiological activity in the autumn and early winter for spruce compared to pine [41], and therefore, in case of persistent wet soil conditions during this period, fine root function may be impaired due to oxygen deprivation, reducing nutrient uptake and leading to imbalances that could affect earlywood formation in the following growing season. During early period pine showed significant positive correlation with SPEI in February-March, while also exhibiting positive correlation with February-March temperatures, implying of warm/wet conditions in these month having positive effect on increment [43]. Pine also exhibited a positive legacy effect of July precipitation during the early period [44], indicating that sufficient water availability in the preceding year had a beneficial impact on increment in the following growing season.

During the later period (1970-2022), a diminished climate-induced growth signal was observed, likely due to the natural deterioration of the drainage network, affecting the water table level. Similar patterns have been reported in neighbouring Estonia, where Scots pine growth became less responsive to climate variables as the rising water table became the dominant growth limiting factor [45]. During the later period, spruce showed a negative correlation between TRW and August precipitation, which remained a significant factor throughout the full period (1917-2022), indicating a substantial effect, despite its non-significance in the early stage. The negative effect of poorly aerated soil conditions for spruce has been reported before [33,34], and is likely related to the reduction of drainage performance with increasing age [46], possibly due to lack of regular maintenance or stand thinning, that can cause the water table level rise due to reduced evapotranspiration potential [47].

Spruce showed significant positive correlation between TRW and SPEI in January in the latter period. Precipitation during this period could be related to increased precipitation in a form of snow cover providing insulating effect, thereby protecting roots from freezing [48].

Conclusions

Weather sensitivity responses of conifer species growing in drained peat soils were complex, predominantly associated with temperature and precipitation patterns. Findings align with other studies reporting positive effect of milder winter and early spring onset for Scots pine, suggesting pine climate-growth responses being similar to those growing in freely draining mineral soil. However, no negative correlations were observed with temperature that would suggest drought stress of spruce during summer months, as reported in other studies conducted on freely draining mineral soils. This suggests that local soil moisture conditions or site-specific hydrological factors may have mitigated the impact of summer drought stress in drained peat soils, suggesting that Norway spruce may remain a viable silvicultural option on drained peat sites even under projected climate change scenarios. However, Spruce showed negative growth responses in the later development stage, reflecting its preference for well-aerated soils and highlighting the importance of maintaining functional ditch networks in drained spruce stands. Therefore, more targeted studies on drained peat soils are needed to improve understanding of species-specific responses and their adaptability to future climate change. These studies should also consider key soil characteristics such as peat thickness, bulk density, and moisture content inter annual variation. Since drainage functionality has a strong influence on soil moisture and, in turn, on tree growth responses to climatic factors, exploring alternative management strategies is essential for enhancing forest resilience. For instance, admixture of birch in spruce stands may mitigate excess soil moisture due to birch high evapotranspiration capacity.

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Author contributions

Conceptualization, R.M., methodology, R.M. and A.J., software, K.B., validation, R.M., investigation, K.B., data curation, D.J., writing – original draft preparation, K.B., writing – review and editing, K.B and R.M., visualization, R.M., K.B., project administration, R.M., funding acquisition, A.J. All authors have read and agreed to the published version of the manuscript.

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