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Tree-ring width and stable isotope analyses of *Picea sitchensis* from Iceland reveal growth potential under predicted climate change

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ABSTRACT

Sitka spruce has been one of the most planted tree species in Iceland since the mid-twentieth century. Here, we use different dendrochronological methods to identify the controlling climatic factors of its growth and possible changes in their influence over time. We develop annually resolved and absolutely dated measurements of tree-ring width (TRW) from 21 trees and oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) stable isotopes from six trees to evaluate growth trends and climate sensitivity in Iceland's Hallormsstaður National Forest over the past 54 years (1965–2018). Warmer and wetter summers in the last few decades have resulted in significantly increasing radial growth. While TRW and $\delta^{13}C$ reflect strong July-August temperature signals, with the highest correlation for July, $\delta^{18}O$ is mainly controlled by the temperature in March. The occurrence of negative pointer years in TRW decreases with increasing temperature in July but increases with excessive precipitation in August. Our study shows great continued potential for Sitka spruce cultivation in Iceland.

Keywords: afforestation, climate change, precipitation, dendrochronology, temperature

YFIRLIT

Mælingar á árhringjabreiddum og stöðugra samsætna í sitkagrein frá Íslandi sýna vaxtargetu við spár um loftslagsbreytingar.

Frá miðri tuttugustu öldinni hefur sitkagreni verið ein af mest gróðursettu trjátegundum á Íslandi. Við notuðum aðferðir árhringjarannsókna til að greina þá umhverfisþætti sem hafa mestu áhrif á vöxt og viðgang sitkagrenis á Hallormsstað og þær breytingar sem hafa orðið á áhrifum umhverfisþátta gegnum árinn. Við byggðum upp tímatal fyrir árhringjavöxtinn með því að mæla breiddir árhringjanna í 21 tré, þannig að hver árhringur fékk sitt ártal og meðalbreidd. Einnig mældum við stöðugar samsætur súrefnis ($\delta^{18}O$) og kolefnis ($\delta^{13}C$) í árhringjum sex trjáa. Þetta var framkvæmt til þess að meta árlegan vöxt og áhrif veðurfars á viðgang trjánna/skógarins. Sýnum var safnað í Hallormsstaðarskógi og nært árhringjatímatalið aftur til ársins 1965 eða síðustu 54 árin (1965–2018). Hlýr og rök sumur á síðustu áratuga hafa leitt til verulegs aukins þvermálsvaxtar í sitkagreninu. Á meðan árhringjavöxtur og $\delta^{13}C$ endurspeglar góða fylgni við sumarhita í júlí–ágúst og hæstu fylgni fyrir júlí hita er $\delta^{18}O$ aðallega stjórnað af hitastigi í mars. Tíðni neikvæðs árhringjavaxtar minnkar með hækkandi hitastigi í júlí en eykst ef águstmánuður er úrkomusamur. Rannsókn okkar sýnir að framtíðarhorfur ræktunar sitkagrenis eru góðar á Íslandi þrátt fyrir væntanlegar breytingar á veðurfari.

INTRODUCTION

Sitka spruce (*Picea sitchensis*) is one of the most important species used for afforestation in Iceland, accounting for 14 % of all trees planted from 1940 to 1998 (Sigurdsson & Snorrason 2000). Afforestation by planting trees, especially exotic spruces, pines and larches, was very intensive in the 1950s and the first half of the 1960s (Blöndal & Gunnarsson 1999, as cited in Reynisson 2011). Planting declined after 1963 when extreme spring frost damaged a large proportion of planted forests in southern and western Iceland. The afforestation programme was restarted at the end of the 20th century (Eggertsson et al. 2008) to increase carbon sequestration in forests, vegetation and soil (Sigurdsson & Snorrason 2000). Sitka spruce plays a key role in afforestation, as it makes up the largest growing stock of any exotic planted tree species (Snorrason et al. 2005).

In June 2020, the Icelandic government published an updated Climate Action Plan (Government of Iceland 2020), an important aim of which was to increase carbon sequestration through improved land use, land use change and forestry. Changing climate conditions can markedly influence the growth and vitality of cultivated forests and consequently amount of carbon sequestration. Therefore, a better understanding of the climate-growth relationship is fundamental for forest carbon stock prediction. It may contribute to improved decision-making about the potential of Sitka spruce for commercial timber production, as well as for carbon sequestration under current and projected Icelandic climatic conditions.

Several tree-ring studies of Sitka spruce have been carried out within the natural distribution of Sitka spruce in North America (Wiles et al. 1998, Barclay et al. 1999), as well as outside its natural distribution, where Sitka has been planted because of its fast growth and relative resistance, e.g., Norway, Iceland, Scotland, Denmark, Poland and Estonia (Feliksik & Wilczyński 2008 & 2009, Vihermaa 2010, Huang 2017, Läänelaid & Helama 2019, Kasesalu et al. 2019, Kuckuk et al. 2021). However, in these studies climate sensitivity was assessed using conventional tree-ring width. Missing from these studies was the exploitation of other tree-ring parameters more sensitive to environmental factors that allow a better understanding of climate change impacts, processes of physiological acclimation, and succession.

Dendrochronological analyses have been carried out in Iceland to examine the effects of climate change on various native species, both trees and shrubs (e.g., Levanič & Eggertsson 2008, Piermattei et al. 2017, Hannak & Eggertsson 2020, Phulara et al. 2022, Frigo et al. 2023, Opała-Owczarek et al. 2024). Our study complements the results of these analyses with findings from non-native *Picea sitchensis.*

We selected one of the oldest forest stands in Iceland, planted in the 1960s, to retrospectively evaluate its radial growth and climate sensitivity in relation to its potential for future planting in sub-Arctic regions. The main aims of our research were i) to evaluate the growth trends of Sitka spruce over the last ~60 years, and ii) to explore its climate sensitivity and limitations using tree-ring width and stable carbon and oxygen isotope ratios of non-pooled, annually resolved tree rings. Our hypotheses were: i) Sitka spruce growth is mainly influenced by the temperature in the growing season; precipitation does not have a significant effect on growth due to relatively high amounts of precipitation; ii) anthropogenic climate change has already led to enhanced radial growth. A better understanding of growth trends and the climate factors driving them can contribute to assessing the potential of Sitka spruce in Iceland, both from an environmental (carbon sequestration) and timber production perspective.

MATERIALS AND METHODS

Study area and climatic data

The *Picea sitchensis* sampling site is located in Hallormsstaður National Forest in East Iceland (Figure 1, Table 1). The forest covers an area of 740 hectares, most of which is dominated by native birch, but there are also cultivated forests of various species and experimental forests. In June 2019, we selected 21 representative dominant trees in the forest stand and measured their height and circumference at breast height (1.3 m above ground level). As a measure of tree crown condition, we further evaluated two basic parameters visually (Cudlín et al. 2001) – total defoliation (%) and discoloration, i.e., yellowing and browning (as a % of the total volume of a crown with discoloration). We evaluated the parameters at intervals of 5 % based on the scale defined by Cudlín et al. (2001) (Table 1).

Table 1. Hallormsstaður sampling site – stand information and mean climatic conditions

Latitude/Longitude	N 65°06'10.5"	W 14°43'42.2"
TREE PARAMETERS	**Min.-Max.**	**Mean**
Tree height	18.4–23.6 m	20.8 m
Circumference at breast height	92–156 cm	120.3 cm
Defoliation	5–25 %	11.7 %
Discoloration	absent	absent
CLIMATE CONDITIONS 1965–2018*	**Min.-Max.**	**Mean**
Annual temperature	1.5–5.2 °C	3.6 °C
May-August temperature	7.0–10.4 °C	8.8 °C
Annual precipitation	332–1,669 mm	833 mm
May-August precipitation	51–340 mm	169 mm

** determined on the basis of data compiled from three meteorological stations*

Climate data from three meteorological stations were available and relevant for the study area (Figure 1). The Hallormsstaður station data are discontinuous for temperature (1965–1989 and 1997–2018) and precipitation (1965–1989

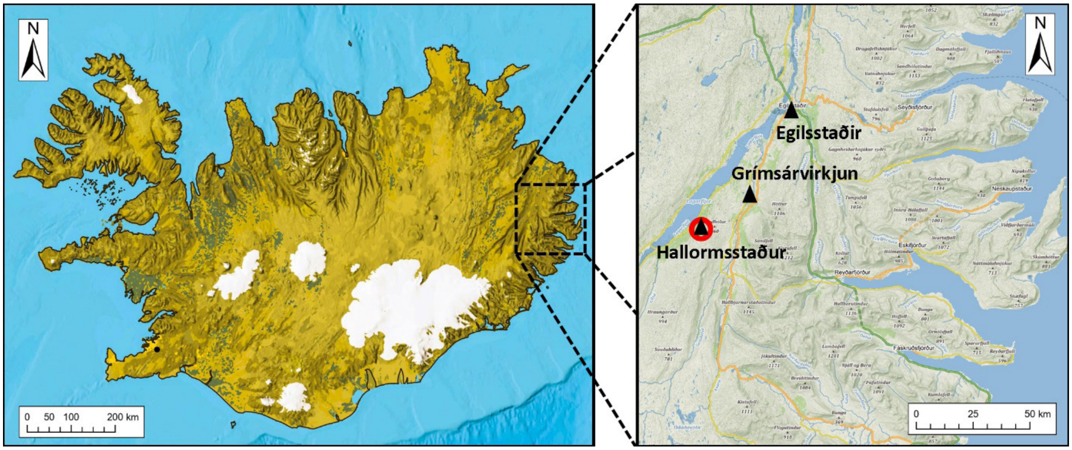


Figure 1. Location of the study site (red circle) and meteorological stations (black triangles). Coordinates of climate stations: Grímsárvirkjun – N 65°08'15.1" W 14°31'56.4"; Hallormsstaður – N 65°05'39" W 14°43'1"; Egilsstaðir – N 65°16'12" W 14°23'32".

and 2002–2018). The Egilsstaðir station data were available only for temperature and cover the whole study period (1965–2018). The Grímsárvirkjun station data were recorded only for precipitation from 1965 to 2013. Since none of the stations provided temperature and precipitation measurements covering the whole study period (1965–2018), we averaged data from the stations into one series for each climate parameter. To verify the average temperature and precipitation data, we compared the averaged station series with climate data from the Climate Research Unit – CRU database (CRU TS4.04; via http://climexp.knmi.nl), which are frequently used in dendroclimatological studies. The comparison shows that CRU data underestimated temperatures and overestimated precipitation, as might be expected in the conditions of Iceland, which are characterised by great spatial variability of climatic parameters (especially precipitation). However, the climate data from both resources are highly correlated (Figure 2). Based on these findings, we decided to use averaged data from meteorological stations for the further analysis.

The climate conditions are characterised by high variability in annual precipitation (with a minimum of 332 mm in 1965 and a maximum of 1,669 mm in 2002), with highest rainfall in November and December (a total of 736 mm in these two months). The annual mean temperature was lowest in 1979 (1.5 °C) and highest in 2014 (5.2 °C). Monthly mean temperatures from December to March were below 0 °C. The warmest months were July and August with mean temperatures slightly above 10 °C.

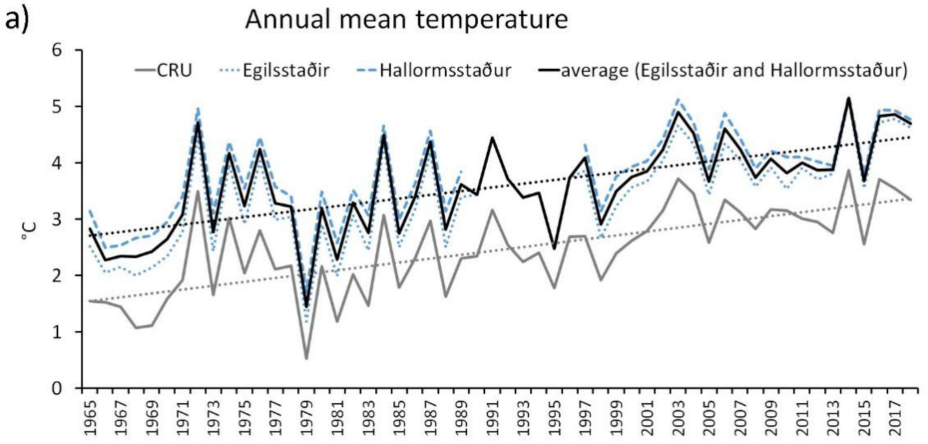
Tree-ring width and stable isotope measurement

We extracted one core per tree at breast height (Kirdyanov et al. 2018) from all 21 selected trees, using a Pressler borer (Haglöf Company Group, Sweden) with a 5-mm inner diameter. Tree-ring width was measured on the cores, using a VIAS TimeTable device with a measurement length of 78 cm (SCIEM, Vienna, Austria). The obtained TRW series were cross-dated and corrected for missing and false rings, using both PAST4 (Knibbe 2004) and COFECHA (Grissino-Mayer 2001, Holmes 1983).

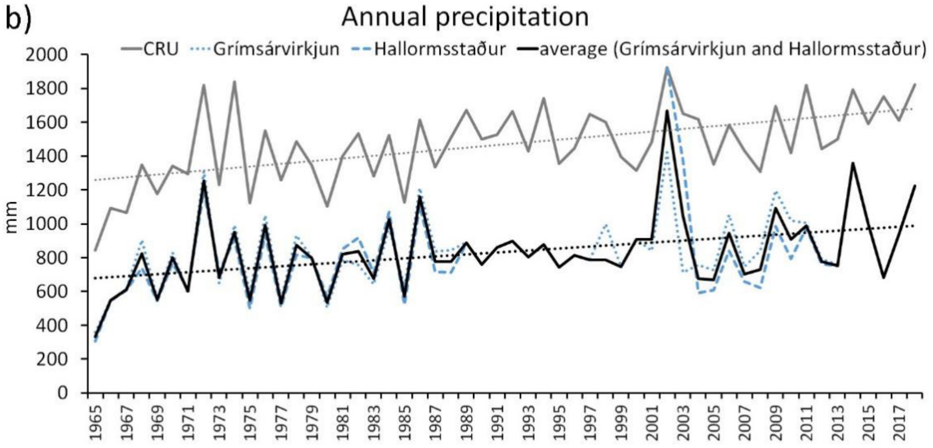
Then, six randomly selected and absolutely dated Sitka spruce core samples were separated with annual resolution. We selected this sample size to maintain sufficient climate signal strength for the isotopic chronologies and in recognition of the financial expense of isotope analysis (Rybníček et al. 2021). Each tree ring was cut into small pieces with a razor blade under a stereomicroscope and packed into F57 Teflon filter bags (Ankom Technology, USA) for alpha-cellulose extraction according to the modified Jayme-Wise isolation method as described in Urban et al. (2021).

The homogenised samples of alpha-cellulose (0.8–1.0 mg) were weighed into tin and silver capsules to determine carbon and oxygen isotopes, respectively. For the $\delta^{13}C$, the alpha-cellulose was combusted to CO_2 at 960 °C, while it was pyrolysed to CO at 1,450 °C for $\delta^{18}O$ measurement using a vario PYRO cube elemental analyser (Elementar Analysensysteme, Germany). The ratios between heavy (^{13}C and ^{18}O) and light (^{12}C and ^{16}O) stable isotopes were determined using an IsoPrime100 continuous flow mass spectrometer (Isoprime, UK). The spectrometer was internally calibrated using certified analytical standards with known isotopic ratios: caffeine (IAEA-600) and graphite (USGS24) for $\delta^{13}C$ and benzoic acids (IAEA-601 and IAEA-602) for $\delta^{18}O$. The $\delta^{13}C$ and $\delta^{18}O$ values (‰) are expressed relative to the Vienna Pee Dee Belemnite (VPDB) and Vienna Standard Mean Ocean Water (VSMOW) standards, respectively. In addition, the $\delta^{13}C$ series were corrected for atmospheric ^{13}C depletion due to fossil fuel burning using a ^{13}C Suess correction model based on Mauna Loa atmospheric CO_2 concentrations (Dombrosky 2020). For further details see Urban et al. (2021) and Römer et al. (2023).

Growth trends of the raw TRW, $\delta^{13}C$ and $\delta^{18}O$ chronologies, as well as the trends of the climatic parameters used (temperature and precipitation), were assessed over the study period (1965–2018), and their statistical



Correlation between temperature series	
CRU – Egilsstaðir	r = 0.979
CRU – Hallormsstaður	r = 0.974
Egilsstaðir – Hallormsstaður	r = 0.990
CRU – average Egilsstaðir and Hallormsstaður	r = 0.979



Correlation between precipitation series	
CRU – Grímsárvirkjun	r = 0.806
CRU – Hallormsstaður	r = 0.791
Grímsárvirkjun – Hallormsstaður	r = 0.793
CRU – average Grímsárvirkjun and Hallormsstaður	r = 0.807

Figure 2. Comparison of CRU climate data and meteorological station data: a) annual mean air temperature with linear trend; b) annual precipitation with linear trend.

significance was determined using the Mann-Kendall test. Pettitt's test (Pettitt 1979) was applied to detect a single change-point in the chronologies, as well as in the meteorological series.

Non-climatic, size- and age-related growth trends and other factors were removed from the individual series by applying four different detrending techniques in Arstan (Cook & Krusic, 2005): cubic smoothing splines with a 50 % frequency response cutoff at 32 and 50 years (spline32, spline50), negative exponential function (neg exp) and regional curve standardisation (rcs). All methods were used to preserve high frequency (inter-annual) variations for climate-growth analysis (Cook & Peters 1981). All indices were calculated as residuals after the adaptive power transformation of the raw data to minimise end-effect problems (Cook & Peters 1997). Chronologies were calculated using bi-weight robust means. Internal signal strength was assessed using inter-series correlation (Rbar) and the expressed population signal (EPS; Wigley et al. 1984). All indexed chronologies, displaying small differences among each other (Figure 3), were used for correlations with climate data (Figure 4).

Since detrending climate data can better capture tree growth sensitivity to climate (Ols et al. 2023), we detrended temperature and precipitation series using the same method as the TRW series. We calculated correlation coefficients between the indexed chronologies and climatic parameters in the period 1965–2018. Monthly values of climatic parameters from January to August of the year of tree-ring formation were considered. The correlations were calculated for monthly values, as well as seasonal means for January-August (the whole year), May-August (vegetation period), and July-August (summer months with expected highest effect). As the best correlation results were obtained using cubic smoothing splines with a 50 % frequency response cutoff at 32 years (Figure 4a, 5), the spline32 chronology was used for further analyses. For the periods with the strongest significant correlations, we performed 19-year moving correlations (window ±9 years) to test the stability of these relationships (Figure 4b).

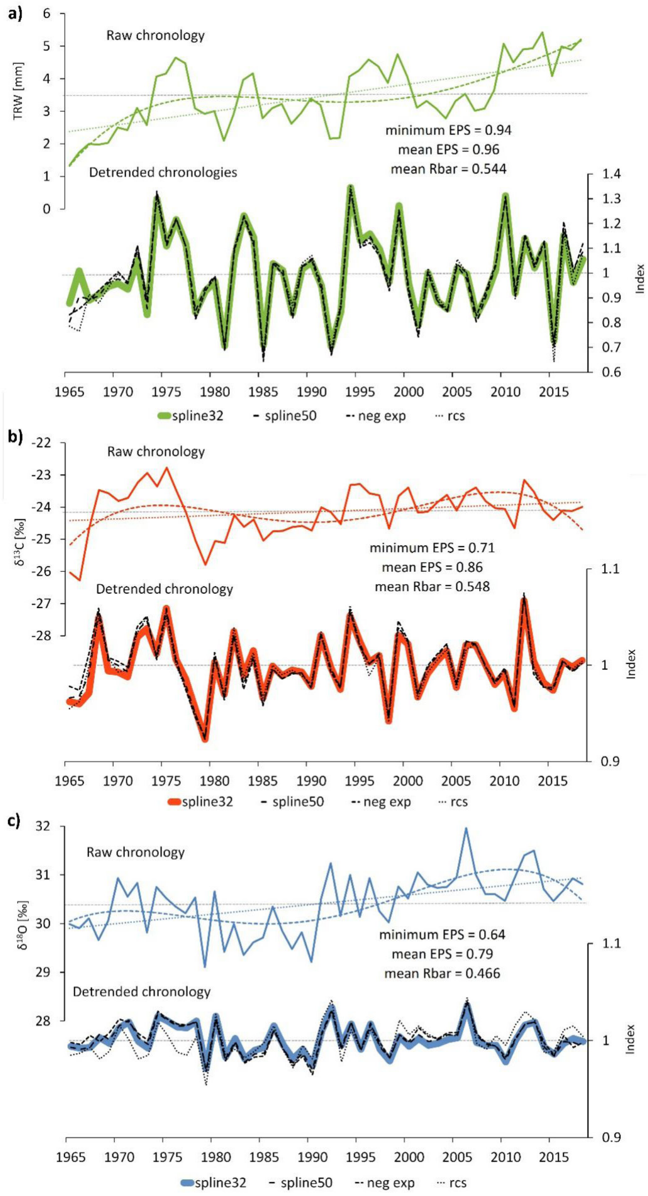


Figure 3. Raw and detrended chronologies (spline32, spline50, neg exp, rcs) of tree-ring width **(a)**, $\delta^{13}C$ **(b)** and $\delta^{18}O$ **(c).** Dashed lines in the raw chronologies are polynomial trend lines, dotted lines are linear trend lines.

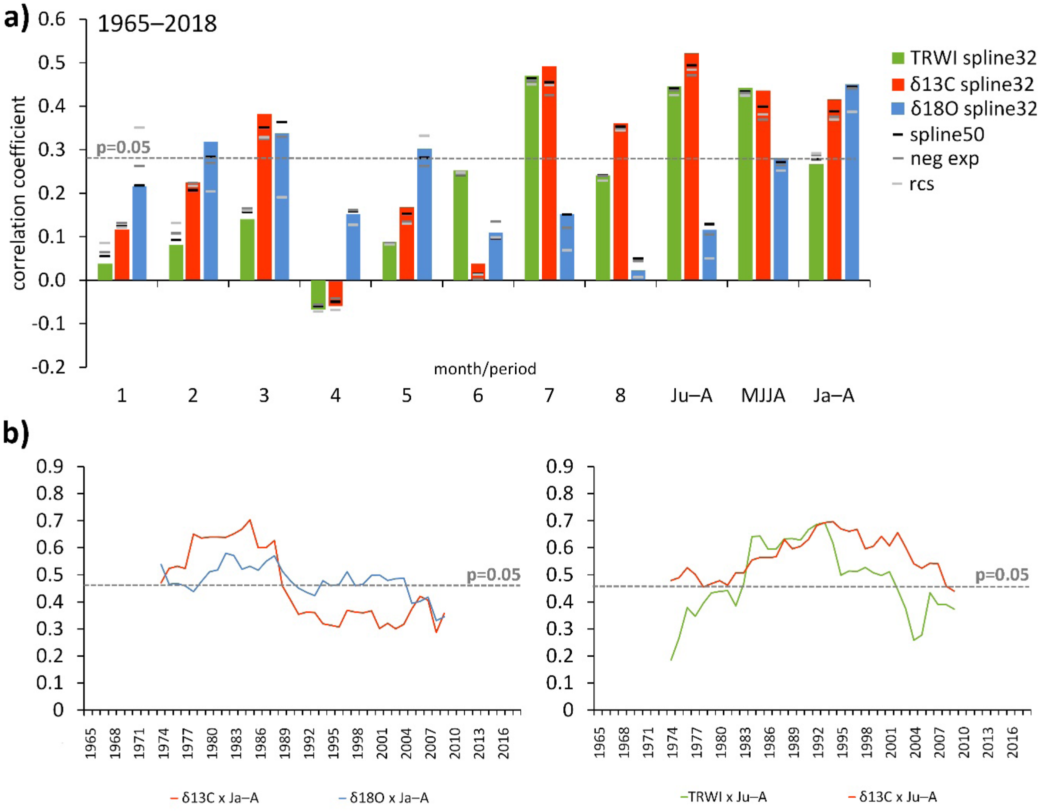


Figure 4. a) Pearson's correlation coefficients between temperature and residual TRW, $\delta^{13}C$ and $\delta^{18}O$ chronologies from 1965 to 2018; **b)** 19-year moving correlation between January-August (Ja-A) temperature and $\delta^{13}C$ (red line) and $\delta^{18}O$ (blue line) and for July-August (Ju-A) temperature and TRWI (green line) and $\delta^{13}C$ (red line).

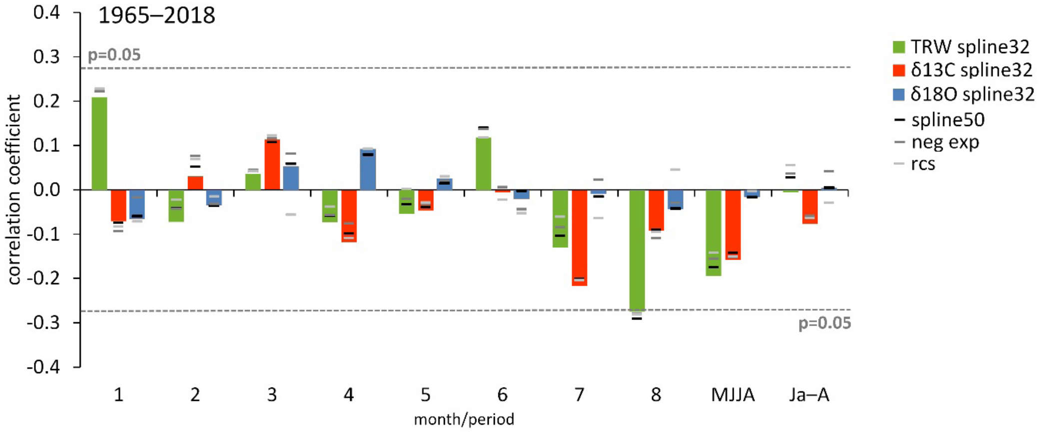


Figure 5. Pearson's correlation coefficients between precipitation and residual TRW, $\delta^{13}C$ and $\delta^{18}O$ chronologies from 1965 to 2018.

Furthermore, negative and positive extremes of tree-ring width chronology were correlated with the climate parameters to determine their influence on the significantly reduced or enhanced radial growth of Sitka spruce trees. The negative/positive extremes were determined for years in which residual TRWI chronology exceeded the ±1.0 multiple of a standard deviation subtracted/added to the mean (Jetschke et al. 2019). The threshold value was arbitrarily defined to yield a sufficient number of extreme years. The relationships between the negative/positive extremes and climate parameters were evaluated using a logistic regression (Quinn & Keough 2002), for which the binary response was coded as a "normal" year (Value 0) or a negative/positive extreme year (Value 1). Models were verified at the first step using Wald's test for regression parameters and goodness of fit (Quinn & Keough 2002). At the second step, only significant models were tested using the likelihood ratio test. The model was considered of merit if both of these tests reached the 0.05 significance level.

RESULTS

Data characteristics

The chronologies covering the period 1965−2018 were replicated by 21 trees for TRW and by six trees for stable carbon and oxygen isotopes. The lowest first-order autocorrelation was observed for the δ^{18}O chronology (0.246), while for the δ^{13}C (0.556) and TRW chronologies it was more than double (0.683), which indicated much greater temporal memory. The highest year-to-year variability, expressed as the mean sensitivity, was observed for TRW (0.228), whereas the values for carbon and oxygen stable isotopes were close to zero (0.036 and 0.028, respectively).

The average tree-ring width varied between 1.34 (1965) mm and 5.43 mm (2014). TRW had a statistically significant increasing growth trend (Mann-Kednall test, S = 681, $p < 0.001$), especially in the last ten years (Figure 3a). Based on Pettitt's test, the significant change point of the linear trend occurred in 1993 ($p < 0.00005$).

The mean carbon and oxygen isotope values were -24.13‰ (δ^{13}C) and 30.42‰ (δ^{13}O), respectively. The standard deviations were 0.74 for δ^{13}C and 0.60 for δ^{13}O. During the study period 1965–2018, stable isotopic chronologies also demonstrated an increasing linear trend (Figure 3b, c), statistically significant for δ^{18}O (Mann-Kednall test, S = 484, $p < 0.0004$) but not significant for δ^{13}C (Mann-Kednall test, S = 191, $p = 0.1563$).

The statistically significant increasing positive trend was also observed for both mean annual temperatures (Mann-Kednall test, S = 694, $p < 0.001$) and for annual precipitation totals (Mann-Kednall test, S = 394, $p < 0.01$) (Figure 2). Pettitt's test revealed the significant change point of the linear trend only for annual mean temperature in 1999 ($p < 0.001$).

Climate sensitivity

We correlated the detrended climate data with the residual TRW, δ^{13}C and δ^{18}O chronologies. TRW and δ^{13}C reflected mainly a positive temperature signal, especially in summer (Figure 4a). The strongest correlations for both TRW and δ^{13}C were identified for July (r=0.470 and 0.492, respectively) and July-August (r=0.446 and 0.522, respectively). δ^{18}O is mainly controlled by temperature in the winter and spring months (mostly March with r=0.337); however, the strongest correlations were identified for January-August temperature (r=0.450).

We made 19-year moving correlations for the period with the strongest correlations (Figure 4b), to assess their temporal variability within a relatively short chronology. The relationship between the July-August temperature and TRWI was statistically significant only during the 1980s and the 1990s, otherwise the correlations were slightly below the significance level. The relationship between the July-August temperature and δ^{13}C was stable and significant for the whole period. The relationship between the January-August temperature and δ^{13}C was above the significance level until the late 1980s, when it dropped and ranged between 0.3 and 0.4. The relationship between the January-August

Table 2. Logistic regression results – relationships between negative pointer years and climatic parameters

Extremes	Climatic parameter	Estimate	Std. error	z value	p (>|z|)	Likelihood ratio test
Negative	Temperature (July)	-0.8069	3.1664	-2.535	0.0395	0.005
	Precipitation (August)	0.0341	0.0127	2.677	0.0074	0.003

temperature and $\delta^{18}O$ was also relatively stable for the whole period; the correlation coefficient values were around the significance threshold.

Precipitation does not play an important role for Sitka spruce growth. None of the three tree-ring parameters showed any significant correlations (Figure 5) except for a relationship between TRWI and August precipitation (r=-0.275).

To assess abrupt growth changes in TRW, positive and negative pointer years were calculated. We identified eight negative pointer years (1965, 1981, 1985, 1988, 1992, 2001, 2007, 2015) and seven positive pointer years (1974, 1976, 1983, 1994, 1999, 2010, 2016). We found two statistically significant relationships between negative pointer years and climatic parameters. The probability of a negative pointer year occurrence decreased with increasing temperature in July and increased with increasing precipitation in August (Table 2). We found no relationship between positive pointer years and climatic parameters.

DISCUSSION

Climatic signals

The natural occurrence of *Picea sitchensis* is associated with hypermaritime to maritime cool mesothermal climate conditions (Klinka et al. 1990), i.e., areas with high annual precipitation and cool moist summers (Franklin et al. 1972, Griffith 1992). The best sites for Sitka spruce have deep, moist, well-drained soils. Hallormsstaður is a cold site with high annual precipitation (Table 1, Figure 2), i.e., it has good conditions for the growth of Sitka spruce. Tree-ring width has an increasing trend, especially in the last ten years (Figure 3a). We found significant positive correlations of tree-ring parameters with temperature in the growing season and the absence of significant correlations with precipitation. The positive effect of summer temperatures on radial growth is confirmed by the observed decreasing probability of a negative pointer year occurrence with increasing July temperature (Table 2). Our findings are consistent with other studies from northern regions, especially from Alaska, where summer temperatures have been identified as a major driver of tree ring development of Sitka spruce, and where precipitation plays only a minor role (Wiles et al. 1998, Barclay et al. 1999). Summer temperatures have been identified as a major factor positively controlling tree-ring width even for plantings in the Southern Hemisphere, specifically on subantarctic Campbell Island (Palmer et al. 2017). However, in areas with higher average temperatures (Poland, Estonia, Scotland, Denmark), temperature often had no effect on tree-ring width (Vihermaa 2010, Huang 2017) or had only negative effect (Vihermaa 2010). If a positive effect was identified for this areas, it was found only for winter and early spring (Feliksik & Wilczyński 2008 & 2009, Läänelaid & Helama 2019). On the contrary, the effect of precipitation on tree-ring width has occurred at the expense of temperature, and in particular, the positive effect of precipitation in the summer months (Feliksik & Wilczyński 2008 & 2009, Vihermaa 2010, Huang 2017, Läänelaid & Helama 2019).

We found increasing trends in $\delta^{13}C$ and $\delta^{18}O$ values and in their significant positive correlations with temperature during the growing season. Values of $\delta^{13}C$ depend on factors influencing the photosynthetic uptake of CO_2 and are primarily controlled by stomatal conductance and the rate of carboxylation during photosynthesis (Farquhar et al. 1989). On the contrary, $\delta^{18}O$ values are closely related to the isotopic composition of the source water and the rate of H_2O transpiration (Barbour & Farquhar 2004). Enhanced transpiration, a process stimulated by high temperature and low relative air humidity, leads to the enrichment of ^{18}O in leaves and subsequently its higher representation in synthesised carbohydrates and cellulose (Porter et al. 2009, Esper et al. 2018). Accordingly, the climatic signal of $\delta^{18}O$ decreases in the cold and wet environments of arctic regions.

It is well known that stomata close under water-limited conditions. The consequent low conductance for CO_2 diffusion through stomata reduces ^{13}C discrimination in plants and leads to changes in $\delta^{13}C$ (Gagen et al. 2004, Porter et al. 2009). In humid conditions, however, the key factors influencing $\delta^{13}C$ are solar radiation and temperature, modulating the photosynthetic activity of the Rubisco enzyme (McCarroll et al. 2003, Gagen et al. 2007, Porter et al. 2009). Therefore, temperature was expected to be the main factor affecting isotope values at the well-watered Hallormsstaður site, and this was confirmed by our analyses.

Studies of the climate sensitivity of tree-ring $\delta^{13}C$ and $\delta^{18}O$ of Sitka spruce are missing. Research on other coniferous trees have shown most frequently a positive correlation with annual or summer temperature, which is in agreement with our findings for Sitka spruce (Figure 4). Positive correlations of summer temperature with $\delta^{13}C$, $\delta^{18}O$ (or both) have been identified for: *Pinus sylvestris* in the French Alps (Gagen et al. 2004), Switzerland (Sauer et al. 2008) and Sweden (Esper et al. 2018); *Abies alba* and *Picea abies* in Switzerland and Germany (Sauer et al. 2008, Weigt et al. 2015); *Picea glauca* in North Canada (Porter et al. 2009); *Larix decidua* in the French and Swiss Alps (Daux et al. 2011, Esper et al. 2020); and *Pseudotsuga menziesii* in Germany (Weigt et al. 2015).

The most significant correlations between temperature and tree-ring parameters were relatively stable over time (Figure 4a). The decrease of the correlation observed between July-August temperature and TRWI at the end of the observation period may be related to the "divergence problem" (described in Brifa et al. 1998). A similar change of positive correlations with summer temperature for *Picea abies* in Norway has been found, when the positive effect of temperature lost its significance after 2000 (Čermák et al. 2019). Some possible explanations relate the divergence anomaly to a response to climate change. Changes in climatic parameters can be non-linear; different variables can have a different course of change. Tree-ring width might be controlled by variables other than average temperature, such as maximum and minimum temperatures (D'Arrigo et al. 2008).

Potential Sitka spruce for forestry in Iceland

Recent studies from Sweden and Iceland show that Sitka spruce grows much better (it has bigger volume production) than Norway spruce in Scandinavia (Tengberg 2005, Reynisson 2011). The high growth potential of Sitka spruce is also shown by individual-tree growth models based on data from permanent sample plots established by the Icelandic Forest Service between 1970 and 2020 (Heiđarsson et al. 2022). When considering its further use in plantings in Iceland, we must take into account some of its problematic properties. Sitka spruce can have a large capacity for spread, as found out Nygaard & Øyen (2017) for coastal Norway, and its stands provide poor habitats for native species of lichen, moss and vascular plants (Elmarsdottir et al. 2008, Bidne 2016). We can expect that some biotic risks will increase as the climate changes. Increasing winter temperatures can promote larger overwintering populations of insect pests – for example, green spruce aphid (*Elatobium abietinum*) – which is an important defoliating pest of Sitka spruce in Iceland, especially in the south and east coastal regions (Blöndal 1987, Day et al. 1998, Kuckuk et al. 2021). For the same reasons, an increase in the occurrence and voracity of some defoliators of other planted conifers can be expected as a result of the extension of the pest ranges towards the north, or the loss of regulatory factors limiting their outbreak areas (Netherer & Schopf 2010, Ammunét et al. 2012).

Our results confirmed a stable radial growth of Sitka spruce in Hallormsstaður, with an increase in the last ten years (Figure 3). As expected, its growth was mainly controlled by summer temperatures (Figure 4). Precipitation was characterised by high interannual variability, but due to its generally high level it did not have a significant effect on the growth of Sitka spruce (Figure 2. 5). Given the current climatic conditions, their expected trends in the future and the ecological amplitude of Sitka spruce, we can expect the species to continue its vital growth. It can also be assumed that low average temperatures in the summer months (especially in July), which increase the likelihood of a negative pointer year, will become less frequent due to advancing climate change. From this point of view, Sitka spruce still appears to be a suitable tree species for cultivation in Iceland. However, its growth potential and reactions to changing climate condition should be assessed again in a few decades, when more stands have reached the rotation age.

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