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## LETTER

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## Post-1980s shift in the sensitivity of tundra vegetation to climate revealed by the first dendrochronological record from Bear Island (Bjørnøya), western Barents Sea

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Tundra vegetation dynamics are an excellent indicator of Arctic climate change. In many places in the Arctic, greening of tundra has been observed since the 1980s due to rapid increases in temperature. However, in some areas the opposite process has taken place in connection with a reduction in biomass production. The spatial patterns of tundra ‘greening’ and ‘browning’ constitute important issues in the contemporary analysis of polar ecosystems. The aim of our study was to assess recent tundra vegetation dynamics on the basis of changes in annual growth ring widths of the polar willow. Bjørnøya (Bear Island), located in the western part of the Barents Sea is an important site in the transition zone between the high and low Arctic. No dendrochronological studies have been conducted to date due to the island’s isolation, which makes access very difficult. In 2012 and 2016, 43 samples of *Salix polaris* Wahlenb. were taken from the south-eastern part of Bear Island. An average chronology of the 29 most closely correlated measurement series was then compiled, covering 95 years (1922–2016); however, the time span 1946–2016 was used for the climate-growth analysis. Beginning in the mid-1980s, an increase in the width of annual increments was observed, whereas over the last decade (since 2005) the growth rate has declined rapidly. Simple correlation analyses showed that temperatures in spring and summer had the positive influence on the radial growth of the polar willow; however, the results of the moving correlation analysis made it possible to conclude that this relationship is more complex and time-dependent. Sensitivity of radial growth to temperature was strongest in the years 1955–2005, whereas the decrease in the strength of positive correlation with temperature since 2005 has been accompanied by a significant increase in the importance of summer precipitation.



In memory of the first year-round Polish Arctic Expedition, Bjørnøya 1932/1933. Photograph of the expedition participants, from the right: Stanisław Siedlecki, Czesław Centkiewicz and Władysław Łysakowski. Reproduced from Narodowe Archiwum Państwowe. Image stated to be in the public domain.

## 1. Introduction

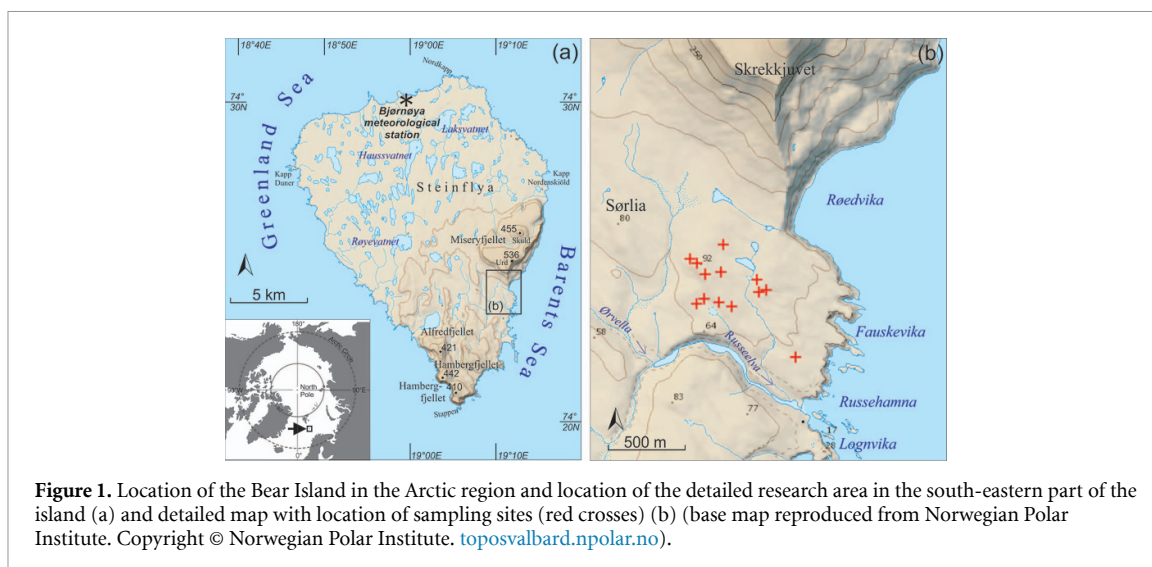
Arctic terrestrial ecosystems are extremely sensitive to modern climate variations and reflect the effects of changes in air temperature, precipitation, snow cover, permafrost, active geomorphic processes, and the frequency or intensity of wildfires. Large-scale warming in the Arctic has accelerated during recent decades and is now occurring at a rate twice that of the global trend (AMAP 2017). However, climatic and inter-annual weather conditions in the Arctic vary spatially, as well as the dynamics of biological, biogeochemical, and geomorphic processes in terrestrial ecosystems. (Raynolds *et al* 2008, Wolf *et al* 2008, Przybylak 2016). Although many Arctic regions have become greener since the 1980s, reflecting the positive response of tundra shrub species to warming and an increase in plant growth ('arctic greening'), satellite data showed a decrease in plant productivity ('arctic browning') in many areas since the early 2000s (e.g. western Siberia, the northern part of the Canadian Archipelago) (Jia *et al* 2003, Bhatt *et al* 2013, Frost and Epstein 2014, Phoenix and Bjerke 2016, AMAP 2017, Epstein *et al* 2017, Lara *et al* 2018, Tømmervik and Forbes 2020).

Dendrochronological research conducted in various polar regions confirmed that *Salicaceae* and *Betulaceae* are characterised by measurable and countable growth rings which boundaries are distinctly marked. Tundra plants growing in Arctic environments are very sensitive to climatic conditions and thus especially useful for dendroclimatic investigations (e.g. Forbes *et al* 2010, Büntgen *et al* 2015, Myers-Smith *et al* 2015a, Owczarek and Opała 2016, Weijers *et al* 2017, Le Moullec *et al* 2019, Opała-Owczarek *et al* 2020). Arctic shrub dendrochronology, the dating of annual growth rings, has been used to reconstruct climate and environmental history over the past few decades (e.g. Schmidt *et al* 2006, Zalatan and Gajewski 2006, Owczarek 2010, Forbes *et al* 2010, Hallinger *et al* 2010, Blok *et al* 2011, Myers-Smith *et al* 2011); however, especially in recent years, an increase in the environmental importance of Arctic dendrochronology research and studies on complex plant response to changing environmental conditions

has been observed (e.g. Buchwal *et al* 2013, 2019, Myers-Smith *et al* 2015a, 2020, Owczarek and Opała 2016, Weijers *et al* 2017, 2018, Martin *et al* 2017, Forchhammer 2017, Opała-Owczarek *et al* 2018).

Many early dendroclimatological studies indicated that shrub growth rates were positively sensitive to summer temperature in most species and at most sites (e.g. Weijers *et al* 2010, Buchwal *et al* 2013). However, more recent studies show that shrub growth/climate relationships are not uniform across the tundra biome (Myers-Smith *et al* 2015a, 2020). In contrast to previous studies, which focused on a single factor such as the influence of summer temperatures, research results for willows from the Svalbard Archipelago in the High Arctic (Owczarek and Opała 2016, Opała-Owczarek *et al* 2018) and Siberia (Blok *et al* 2011) also highlighted the sensitivity of shrub growth to soil moisture and precipitation.

Numerous stress factors, e.g. drought, mechanical damage caused by frost, abrasion from wind-transported particles (sand, snowflakes), geomorphic/periglacial processes, changes in permafrost, insufficient soil nutrient content, and animal grazing, can reduce radial growth (Grime 1979, Owczarek *et al* 2013, 2014, AMAP 2017, Opała-Owczarek *et al* 2018). However, it should be noted that, due to the multiplicity and complexity of these factors, the causes of browning trends remain unclear (Reichle *et al* 2018). Heretofore, this process has been most frequently analysed from either satellite-derived observations (e.g. Lara *et al* 2018) alone or detailed ground-based ecological analysis limited to individual locations (e.g. Callaghan and Tweedie 2011). Taking these research problems into account, we pose the following main questions: (a) how has modern climate change influenced tree-ring variability in dwarf shrubs on Bear Island? (b) Does temporal variability in tree-ring patterns and climate sensitivity on the island align with the recent and commonly reported shift from greening to browning of the vegetation in the Arctic region? To answer these questions, we used dendrochronological methods to investigate polar willow growth rings on an unexplored Arctic island from the point of view of dwarf shrub wood anatomy and ecology.



## 2. Material and methods

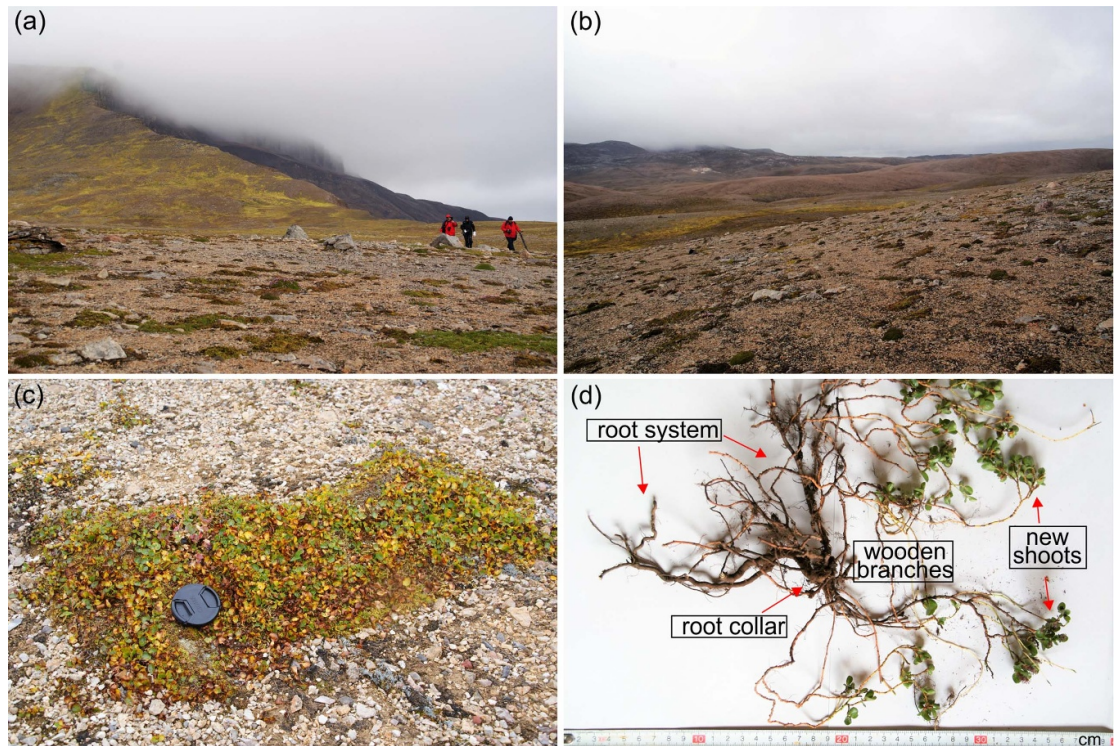
### 2.1. Study area

Bear Island (Bjørnøya) is the southernmost island of the High Arctic Svalbard archipelago located in the western part of the Barents Sea. This isolated island, situated midway between the Scandinavian Peninsula and the rest of the archipelago, is approximately 20 km long, with a maximum width of 15 km (figure 1(a)). The northern and western parts of the island are covered with lakes and characterised by flat and slightly hilly topography. The rest of the island is mountainous, its highest point being Miseryfjellet (536 m a.s.l.), with steep sea cliffs reaching 400 m in height. The relief is clearly related to geological structures consisting of sedimentary rocks (Worsley *et al* 2001). The southern part is built of a Late Proterozoic—Ordovician folded basement composed mainly of dolomite, the rest of the island of Devonian—Triassic conglomerates, sandstones, and limestones. The sampling sites were located in the south-eastern part of the island at the southern foothills of the Miseryfjellet and Skrekkinvet cliffs, at a short distance from the coast of the Barents Sea (figures 1(b), 2(a) and (b)).

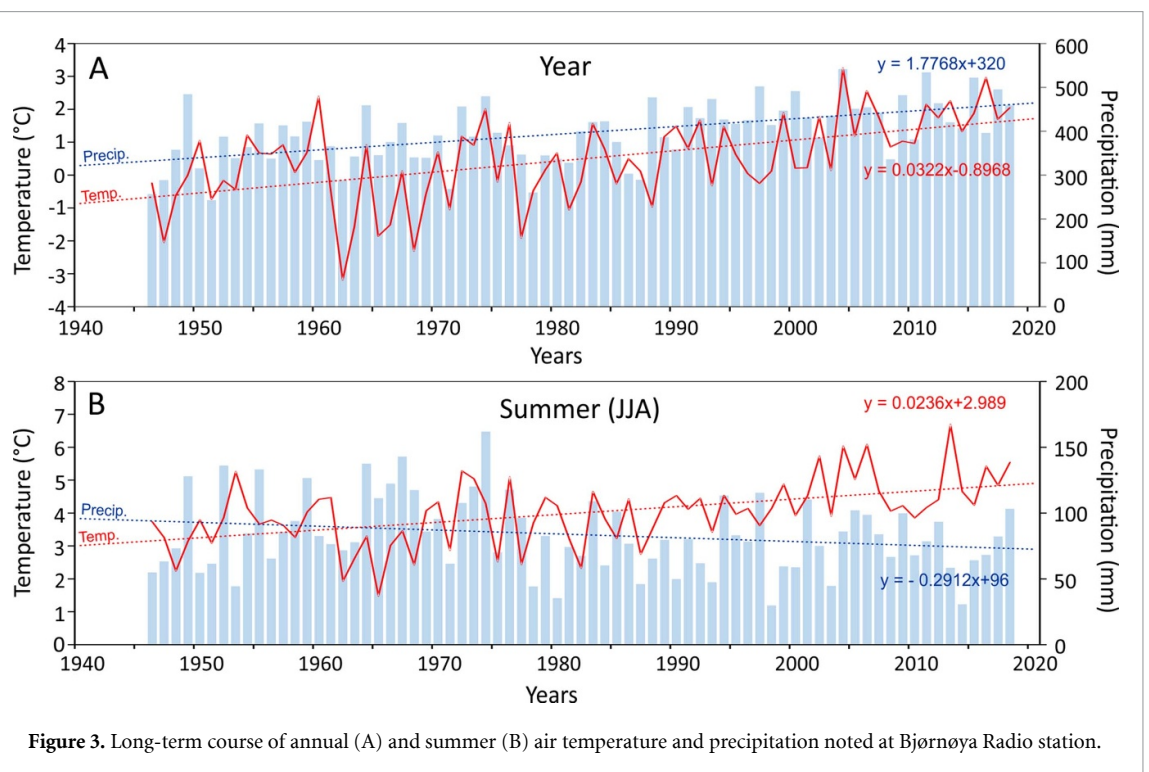
Bear Island is characterised by a maritime-polar climate, shaped by the influence of North Atlantic current, with relatively mild temperatures during the winter. The mean annual air temperature at the Bjørnøya weather station (the unique long-term measuring station that has ever been installed on the island) has varied from  $-5.43$  °C (in 1969) to  $1.81$  °C (in 2016), averaging  $-1.39$  °C (1946–2018). The fluctuations in temperature over the past 100 years are typical of the entire Atlantic sector of the Arctic; nevertheless a warming trend, especially pronounced in recent decades, can be observed (figure 3(a)). Førland and Hanssen-Baur (2000) calculated that linear trends in recorded temperatures in the period 1946–75 amounted to  $-0.29$  °C per

decade, whereas in 1976–2000 these trends have already reached  $+0.49$  °C per decade. Since the beginning of the 21st century, increases in temperature have accelerated, equalling  $1.09$  °C (2000–18), similar to the early period of observations, 1922–40 ( $0.73$  °C per decade). The annual total precipitation in this area is  $396.4$  mm  $\text{yr}^{-1}$  (1946–2018) and has increased over the study period (17.8 mm per decade) (eKlima 2019) (figure 3(a)). However, it should be noted that despite the annual increase, the amount of precipitation in the summer months has been decreasing over the past few decades (figure 3(b)). The coldest month is March, at  $-6.41$  °C, and the warmest is August, with an average temperature of  $4.97$  °C (figure 4). Fog is frequent on the island in the summer, reducing sunlight, along with strong winds influencing the thinning of snow cover and intensive abrasion (Engelskjøn 1986).

Bear Island is classified as being situated in the middle Arctic tundra zone (Elvebakk 1985, 1994). Climate characteristics, nutrient supply, and topography strongly affect plant distribution on the island. Extensive areas are covered mainly by non-vascular communities, in which herbs and dwarf willows are insignificant (Engelskjøn 1986). A large part of the island is covered by seasonally flushed (*Phippisia concinna* Lindeb.) and waterlogged (*Dupontia psilosantha* Rupr.) communities. An important role in vegetation distribution is played by seabird colonies, influencing the fertilisation of nutrient-poor polar terrestrial ecosystems (Zwolicki *et al* 2016, Żmudczyńska-Skarbek *et al* 2017) and the development of ornithogenic maritime tundra communities (*Cochlearia groenlandica* L.) (figures 2(a) and (b)). In well-drained carbonatite areas, especially along the coast and at higher elevations covered by loose rocky material, *Salix polaris* Walenb. and *Salix herbacea* L. communities are dominant (Engelskjøn and Schweitzer 1970, Engelskjøn 1986) (figure 2(c)).



**Figure 2.** General view of sampling sites with isolated polar willow mats at the southern foothills of Miseryfiellet and Skrekkujuvet cliffs in the south-eastern part of Bear Island, intense green indicates the presence of ornithogenic maritime tundra communities (a) and (b); the typical prostrate growth form of polar willow (c); example of polar willow with the basic parts taken to the laboratory analysis (d).

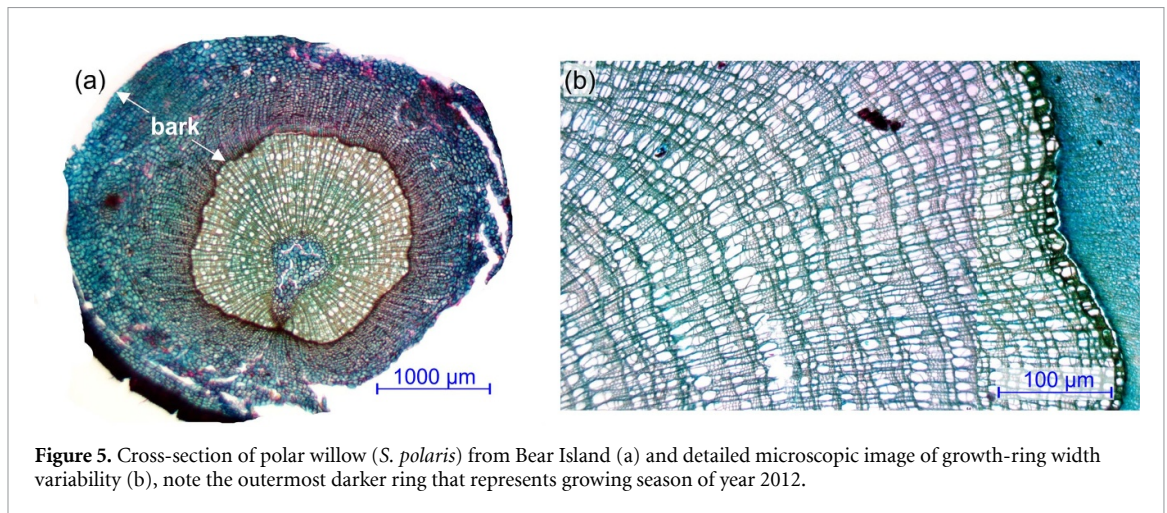
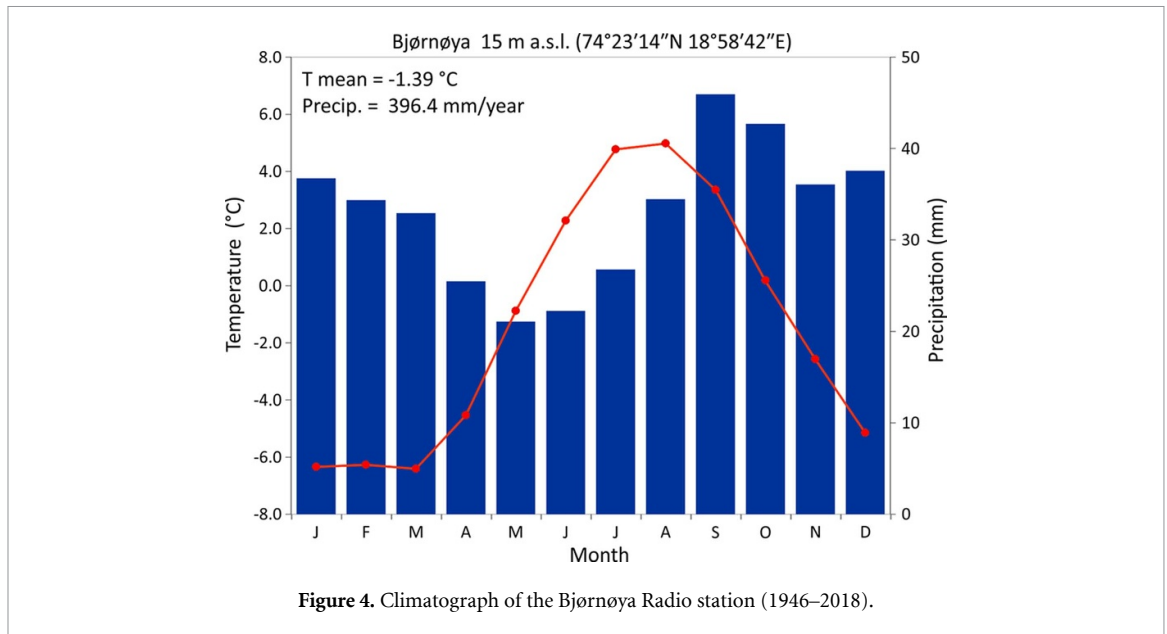


**Figure 3.** Long-term course of annual (A) and summer (B) air temperature and precipitation noted at Bjørnøya Radio station.

## 2.2. Wood material

Polar willow (*S. polaris*) samples were collected from elevations of 56–81 m a.s.l. in the area between Russeelva Valley and Miseryfiellet in the south-eastern part of Bear Island (figure 1(b)). In total,

43 samples of *S. polaris*, including roots, root collars, and wooden branches (figure 2(d)), were collected in the field during a Polish Academy of Sciences polar expedition in 2012 and resampled in 2016. Careful sampling strategy was crucial in our



research. Most of the island is covered by water bodies with varying water levels (see figure 1(a)). We chose an area located several dozen meters above sea level, where there is no possibility of water stagnation (see figure 1(b)). In order to minimise the influence of non-climatic factors on the growth-ring width variability, we collected samples from flat areas without clear traces of periglacial and geomorphic processes. Individuals growing within active solifluction lobes and loose rock particles were excluded from sampling. The sampling area was homogeneous in terms of geological structure and vegetation cover. Plants were collected from the largest mats in the designated research area, which suggested finding the oldest specimens. This strategy proved to be successful in dendrochronological research of polar willow in southern Spitsbergen (Owczarek *et al* 2013, Owczarek and Opała 2016).

Polar willow forms extensive mats, as it does throughout the Svalbard archipelago (Rønning 1996, Owczarek and Opała 2016), sometimes along with

other species, e.g. saxifrage and various species of mosses. This species is extensively distributed on the Bear Island, reaching elevations up to 250 m a.s.l. (Engelskjøn 1986). Intermediate forms between *S. polaris* and *S. herbacea* are commonly found on the island (Engelskjøn and Schweitzer 1970, Engelskjøn 1986, Rønning 1996). These hybrids often grow along with *S. polaris* within the same carpet. The analysed species is characterised by long, creeping roots which grow in shallow soil to depths of 5–10 cm. The short, twisted root collar is located underground or lies partially on the surface. The stem and dense wooden branches lie partly in the upper part of the soil or in the moss carpet. Only small green leaves with new short green shoots are visible above the ground (figure 2(d)). The stem diameter in collected samples ranged from 0.5 cm to an extreme of 1.8 cm. The characteristic feature of the species is thick bark, which often comprises 50% of the cross section (figure 5(a)). Growth rings were well defined, with boundaries

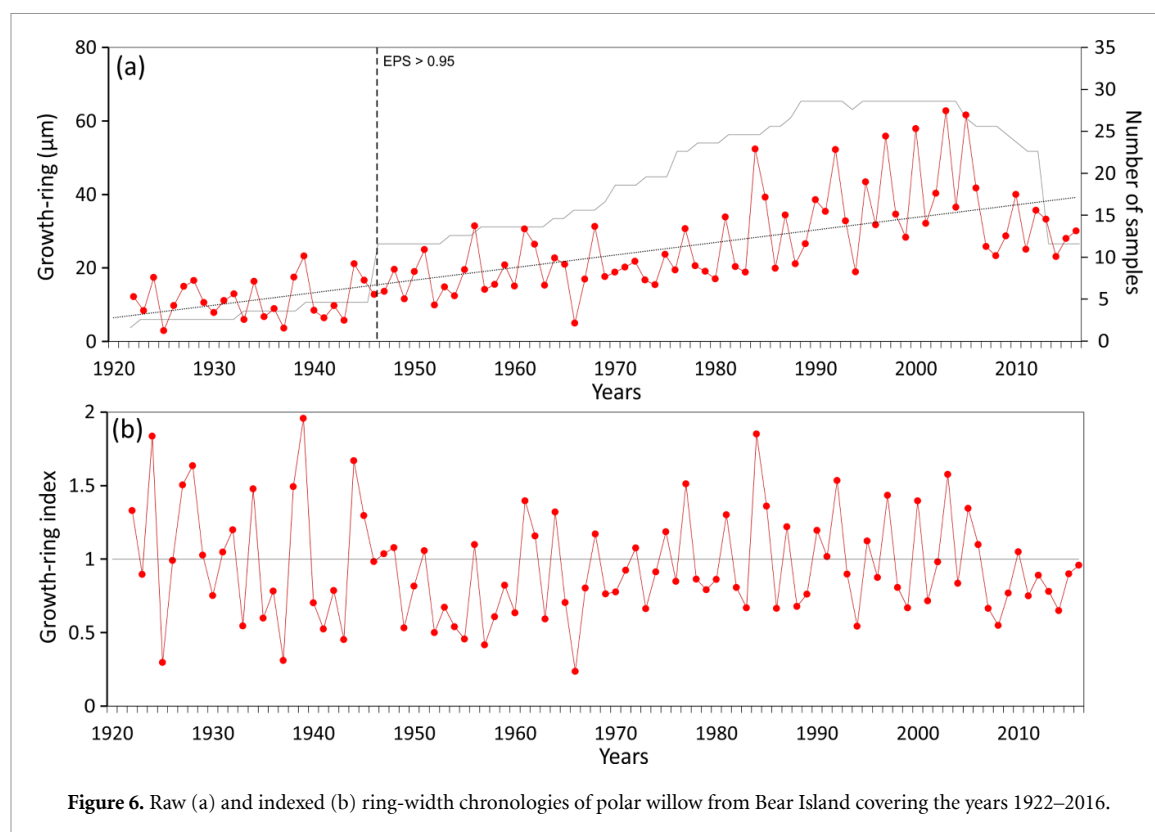


Figure 6. Raw (a) and indexed (b) ring-width chronologies of polar willow from Bear Island covering the years 1922–2016.

delimited by one row of cells or more. Growth-ring widths in the collected individuals ranged from relatively wide ( $190\ \mu\text{m}$ ) to extremely narrow (less than  $10\ \mu\text{m}$ ). Partially or completely missing growth rings were common in the analysed species (figure 5(b)).

In accordance with serial sectioning technique, sampling and measurement of cross sections were performed at several locations below- and above-ground on the same individual, enabling proper age determination and more accurate growth chronology construction (Kolishchuk *et al* 1990, Myers-Smith *et al* 2015a). In the succeeding steps, microscopic slides were prepared in accordance with standard procedures for dwarf-shrub preparation (Gärtner and Schweingruber 2013). Digital photographs of each sample were taken under a microscope. A mosaic of pictures was formed using PTGui software. Due to the large number of wedging and missing rings, at least two radii were measured for each microsection under visual control, using the WinDENDRO tree-ring measuring system (Regent Instruments 2014). All growth-ring measurements were first visually cross-dated and then statistically tested using COFECHA software (Holmes 1983). Poor quality samples with large number of missing rings, significant eccentricity, numerous wedging rings, scars or clearly visible reaction wood were excluded from further analyses. Some samples did not present any apparent age-related growth trend; we therefore applied individual series standardisation including linear regression and horizontal means,

with the choice of function based on best fit for each series, an approach commonly used in dwarf-shrub detrending (Myers-Smith *et al* 2015b, Young *et al* 2016). Well correlated with each other ( $r > 0.4$ ), individual radial growth curves were transformed into dimensionless ring width indices as ratios, averaged and a pre-whitened overall site chronology was constructed for subsequent analyses.

### 2.3. Dendroclimatological analysis

Climate-growth analysis was based on bootstrapped correlation coefficients. Calculations were made using growth-ring index chronology and monthly resolved climatic data from May of the previous year ( $t-1$ ) to September of the current year ( $t$ ) over the period 1946–2016. This time period was selected because expressed population signal (EPS) exceeds the threshold value 0.95. Seasonal data concerning the period from March to September (MAMJJAS) were also taken into account. In the analysis, we used meteorological data from the Bjørnøya Radio station, available from the database of the Norwegian Meteorological Institute. Although meteorological measurements in the station have been carried out since the 1920s, we used a continuous measuring series beginning in 1946. To evaluate the temporal stability of climate-growth relationships, we compared climate and dendrochronological data using a univariate moving window correlation analysis with a 21 year moving interval and 1 year offset. Two climate variables, monthly precipitation and temperature, were considered separately for analysis.

**Table 1.** Site information and growth-ring chronology statistics.

Site code	Location (latitude, longitude)	Elevation (m a.s.l.)	Shrubs/radii	Time span (AD)	MM (SD) <sup>a</sup>	MS <sup>b</sup>	Rbar <sup>c</sup>	EPS <sup>d</sup> > 0.95
BJN	74° 23' 43" N 19° 09' 32" E	56–81	43 (29)/ 129	1922–2016	33.5 (21.7)	0.572	0.552	1947

<sup>a</sup>MM—Mean measurement, SD—standard deviation, <sup>b</sup>MS—mean sensitivity, <sup>c</sup>Rbar—mean running correlation coefficient,

<sup>d</sup>EPS—expressed population signal.

### 3. Results

The oldest individual of *S. polaris* collected during field research was 94 years old. On the basis of dendrochronological dating of the collected specimens, the average chronology was composed of the 29 sequences (figures 6(a) and (b)). Strong signals common to individual ring-width series were confirmed by the results of cross-dating. The remaining 14 samples were rejected due to potential non-climatic growth disorders and growth-ring disturbances. The average correlation between samples used to build the chronology was 0.552 (table 1). The constructed dendrochronological scale covers time span 1922–2016, with a very low radial growth rate (average value = 23.17  $\mu\text{m}$ ) (figure 6(a)). The period with >3 samples and EPS > 0.95 covers the last 70 years and was used as a basis for dendroclimatological analysis.

The course of the annual growth chronology of polar willow indicates the existence of short periods of little growth, e.g. in 1941–44, 1952–54, and 1969–74, whereas in the 1980s and 90s an increase in tree-ring width level and variability was observed (figure 6(a)). The average width of growth rings in this period was 43.82  $\mu\text{m}$ . Next, rapid growth reduction occurred at the beginning of the 21st century (figure 6(a)). In the period 2005–16, the average width of annual increments decreased to 30.38  $\mu\text{m}$ , suggesting that since 2005 there has been a change in growth conditions and a decline in the radial growth of polar willows. Absolute growth rate of *S. polaris* has changed in the analysed period and coincides with periods of higher tree-ring variability. In the years 1946–1980 absolute level of growth-ring width ranged from 5.23–30.27  $\mu\text{m}$ . Since the 1980s absolute growth increment rates variability have been increasing. Absolute growth rates ranged from 17.01 to 61.56  $\mu\text{m}$  in the years 1980–2005. After 2005 the absolute growth decreased and ranged from 25.72 to 41.68  $\mu\text{m}$  (figure 6(a)).

The variability of growth in willows was most sensitive to growing season temperature, with significant positive correlation with spring and summer months (May–September, figure 7). Minimum temperatures were slightly more important at the beginning of the growing season (May–June) ( $r = +0.47$  to  $+0.49$ ) (figures 7(a) and (c)),

maximum temperatures during the late summer ( $r = +0.37$  to  $+0.43$ ) (figure 7(d)). Radial growth was less sensitive to monthly precipitation with statistically significant correlation only for single months: current year February ( $r = +0.40$ ), April ( $r = +0.49$ ), and August ( $r = +0.30$ ) and previous year May ( $r = +0.41$ ) and June ( $r = -0.28$ ) (figure 7(b)).

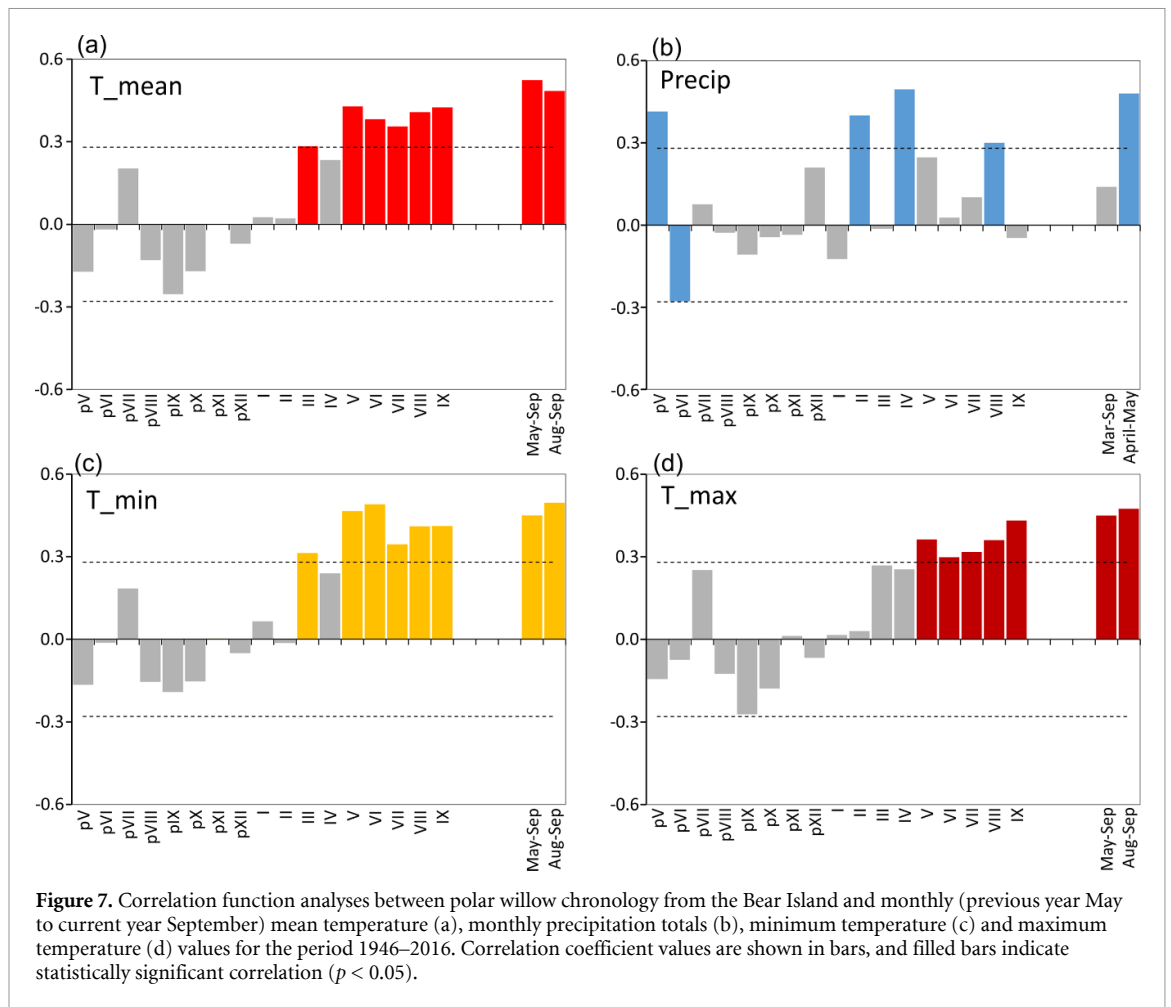
The moving correlation analyses, using 21 year windows, showed a greater sensitivity to spring and summer temperatures on the growth rate of polar willows, from the 1954–75 to 1986–2007 windows ( $r = +0.41$  to  $+0.66$ ). The sensitivity to precipitation shifted from being insignificant to significant positive over the most recent years of the study period. Since the 1987–2008 window, statistically insignificant; meanwhile, the role of rainfall has been increasing ( $r = +0.43$  to  $+0.50$ ) (figure 8). High absolute growth increment rates variability in the period 1980–2005 coincides with higher sensitivity to temperature, while reduction of growth-ring width and lowering of absolute growth rates after 2005 is associated with a moisture deficit and higher sensitivity to precipitation (figure 8).

### 4. Discussion

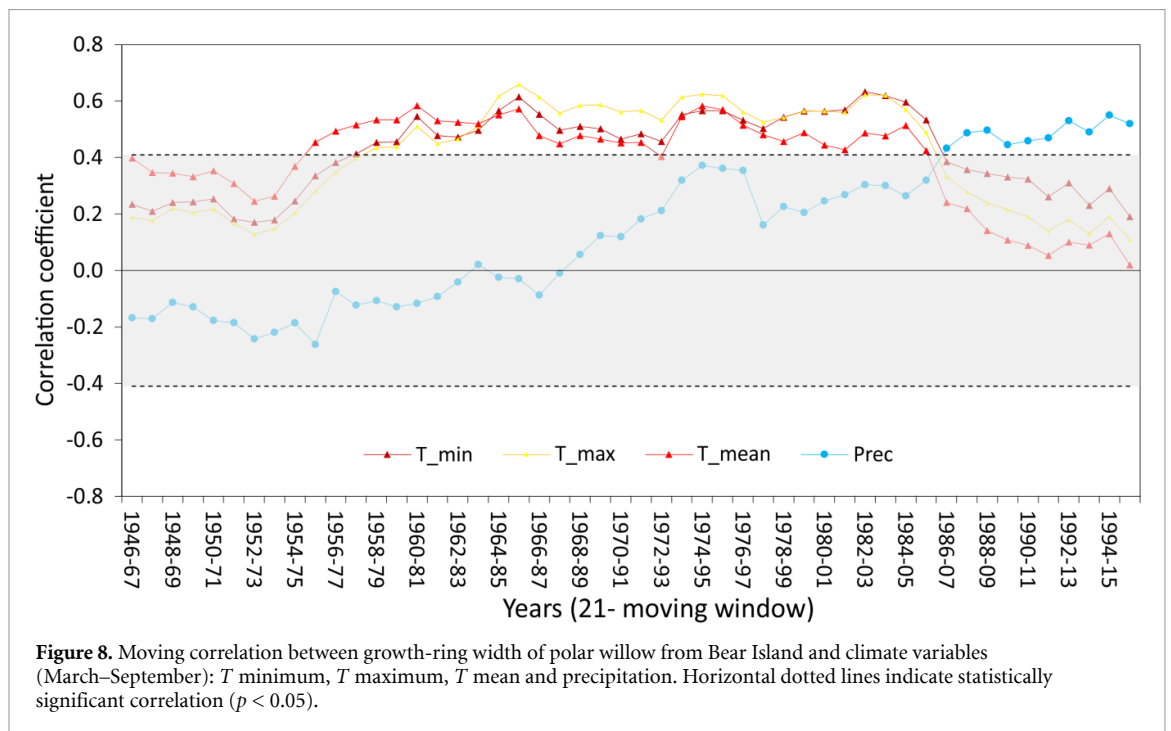
Our preliminary research results, based on *S. polaris* samples collected at one site located in the south-eastern part of the Bear Island, show the possibility of creating new dendrochronological scale in the Arctic. This scale clearly indicates post-1980s shift in the growth trend associated with climate change. There is no published data, which can show and acknowledge the contemporary browning trends in the Bear Island. However, we fulfil the postulate of the AMAP (2017) report on the need to conduct direct research, which may confirm indirect satellite data. We realise that more detailed research across the island is needed to confirm our findings.

The recent increased interest in Arctic dendrochronology is connected with studies on the response of complex tundra plants to changing environmental conditions in the world's most rapidly warming biome (Owczarek et al 2013, Myers-Smith et al 2015a, Owczarek and Opala 2016, Forchhammer 2017, Opala-Owczarek et al 2018). Attempts to use Arctic dendrochronology as a tool for climate reconstruction are limited by the age of tundra plants.





**Figure 7.** Correlation function analyses between polar willow chronology from the Bear Island and monthly (previous year May to current year September) mean temperature (a), monthly precipitation totals (b), minimum temperature (c) and maximum temperature (d) values for the period 1946–2016. Correlation coefficient values are shown in bars, and filled bars indicate statistically significant correlation ( $p < 0.05$ ).



**Figure 8.** Moving correlation between growth-ring width of polar willow from Bear Island and climate variables (March–September):  $T$  minimum,  $T$  maximum,  $T$  mean and precipitation. Horizontal dotted lines indicate statistically significant correlation ( $p < 0.05$ ).

The most extensive climatic reconstruction compiled to date, spanning 180 years, used a ‘tree-ring-like proxy’ based on the annual length of shoot growth

in Arctic bell-heather (Weijers *et al* 2010). According to Schweingruber and Poschlod (2005), polar dwarf shrubs reach ages of 50–140 years. The most extensive

record of High Arctic polar willows was compiled for the Spitsbergen-Hornsund area by Owczarek *et al* (2013) and Owczarek and Opała (2016), who confirmed that the age of an *S. polaris* specimen may exceed 105 years. In the present study, using serial sectioning and cross-dating methods, we determined the age of the oldest *S. polaris* specimen on Bear Island at 94 years. The sites on this island are unique due to the island's great isolation and virtual absence of any human or animal-grazing impact. It is highly likely that older specimens can be found. Continuing this research in the future would be very valuable, as further field sampling may lead to the development of another dendrochronological dwarf-shrub series over 100 years long for the European Arctic. New sampling could also capture more recent growth trends and responses to climate. They will also allow to test if the current higher sensitivity to precipitation in the face of warming is a short or long-term phenomenon.

In general, the positive effects of warming on plant growth are well documented in studies from different parts of the Arctic (Forbes *et al* 2010, Van der Wal and Stien 2014, Myers-Smith *et al* 2015a, Weijers *et al* 2017, Ackerman *et al* 2018, Bjorkman *et al* 2018). The increased productivity of vegetation and shrub expansion, as has been clearly described, is known as 'shrubification', which has led to 'Arctic greening' (Elmendorf *et al* 2012, Macias-Fauria *et al* 2012, Vickers *et al* 2016). This process appears to have reversed since the beginning of the 21st century, when narrow growth rings, which may be related to tundra browning, started to develop. At this point, a positive correlation with precipitation during the growing season, which may indicate drought and water deficiency in soil, became dominant. A similar hypothesis was developed and confirmed in multidisciplinary work conducted in the area of the Fuglebergsletta coastal plain, in the vicinity of the Polish Polar Station in SW Spitsbergen (Opała-Owczarek *et al* 2018). The impact of drought on tundra vegetation is determined not only by changes in precipitation but also by the influence of permafrost and a rapid increase in the thickness of active layer over recent decades. Horn and Orvin (1928) and Theisen (1997) reported that the permafrost on Bear Island is 65–70 m thick; during summer it thaws to a depth of 1 m, but modern time series show general increases in the depths of active layer and rising of permafrost temperatures in the Nordic area (Christiansen *et al* 2010). Contemporary monitoring on Svalbard indicates that temperatures in the upper part of the permafrost rose by 0.7 °C per decade on average during the period 1998–2014, with accelerating speed over the past decade. The active layer has become 25–30 cm thicker since 1998 (Ask and Routti 2017). These conditions signify that, when winters are shorter and less snowy, water from the melting snow cover quickly penetrates the ground and the soil surface dries out.

The increase in the frequency of winter thaws after 2000 has also caused significant changes in the snowiness of winters (Vikhamar-Schuler *et al* 2016). The duration of the snow cover is shorter and water supply from snow is smaller, which is important in the initial growing season. Progressive warming and insufficient amounts of spring meltwater result in higher sensitivity of annual growth rate of *S. polaris* to precipitation (figure 8). This relationship can be confirmed by the previous report of Opała-Owczarek *et al* (2018). In warmer and faster thawing permafrost, the water from snowmelt is less available to the vegetation, as it escapes into the ground early. In the case of Bear Island, precipitation of warm half-year and fog deposits have become essential to growth of vegetation in the spring months. Consequently, the role of precipitation has become increasingly important for *S. polaris* in recent years, as described for this species in southern Spitsbergen (Owczarek and Opała 2016, Opała-Owczarek *et al* 2018) and Siberia (Blok *et al* 2011). With the continuation of the current trends towards increasing temperatures and decreasing summer precipitation, drought stress may grow worse, exacerbating the phenomenon of 'tundra browning' and excessive drying. Our results may prove a valuable contribution to the discussion on the causes of rapid changes in tundra ecosystems due to changes in water supply. Other research results attribute 'Arctic browning' to extreme warm spells in winter, causing rain-on-snow events (Bokhorst *et al* 2009, Bjerke *et al* 2014, 2017, Owczarek and Opała 2016, AMAP 2017, Peeters *et al* 2019). Vikhamar-Schuler *et al* (2016) described changes in winter warming events in the Nordic Arctic Region. These episodes significantly affect the functioning of the polar environment, leading, among other things, to vegetation browning. These authors point out two such important periods in the last century, both characterised by high frequencies of warm weather events, during the 1920s–30s and the past 15 years (2000–14). Icing and ground-ice accumulation are effects of winter thaws, that can cause physical damage to plants. The authors call attention to two spectacular events, one in 2006 and the other in 2012, which had a negative effect on the biotic environment of Svalbard. Such exceptionally warm periods are caused by the inflow of warm Atlantic water into the Nordic Seas, which has a strong influence on climatological processes in this region (Walczowski *et al* 2012).

Many factors influence the process of browning and greening and its variation in time and space. In order to fully understand the transition of tundra from greening to browning in both time and space, we need much more data and direct measurements. The terrestrial productivity of tundra throughout Svalbard exhibits strong overall and local/sub-regional diversity in terms of type of vegetation and the activity of abiotic components such as topoclimatic

conditions or sea-ice concentration (Macias-Fauria *et al* 2017). On the basis of a 30 year period (1986–2015), positive trends in both maximum NDVI (Normalized Difference Vegetation Index) (average increase of 29%) and mean summer temperature (59%) were observed in Central Spitsbergen. However, as also recently reported for lower latitudes, the strength of the year-to-year correlation between maximum NDVI and mean summer temperature has decreased (Vickers *et al* 2016, Reichle *et al* 2018). This suggests that a new trend may be appearing throughout the European Arctic islands, as has been evident in recent years in the reduction in the number of dwarf shrubs compared to bryophytes (Cooper *et al* 2019) or decreases in the widths of annual growth rings (Owczarek and Opała 2016, Opała-Owczarek *et al* 2018). Our results suggest possible decreases in biomass production, based on direct dendrochronological analysis of dwarf shrubs growing on Bear Island.

## 5. Conclusions

The Bear Island site, located in a transition zone between the Low and High Arctic, previously represented an unexplored research gap in Arctic dendroclimatology. We have demonstrated that, despite challenging sampling and cross-dating, it is possible to build a near-century-long chronology of polar willow, one of the longest created in the Arctic region. The island, located in the western Barents Sea between Scandinavia and the main part of the Svalbard archipelago, offered a unique opportunity for dendrochronological analysis without human or animal-grazing impact, yielding reliable information about the effect of climate change on the tundra biome. We found significant positive correlations with summer temperature and spring precipitation signal in the ring-width chronology; however, the correlations have changed over time. Relatively wide growth rings were developed during the 1980s and 90s in response to a rapid increase in temperature. Since 2005, a sharp decrease in the width of growth rings has been observed, indicating a reduction in biomass production. During this time the influence of air temperature on ring-width formation has become non-significant while a significant positive sensitivity to precipitation has emerged. Such recent sensitivity to precipitation may highlight a possible ongoing transition of tundra from greening to browning.

## Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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## References

- Ackerman D E, Griffin D, Hobbie S E, Popham K, Jones E and Finlay J C 2018 Uniform shrub growth response to June temperature across the North Slope of Alaska *Environ. Res. Lett.* **13** 044013
- AMAP 2017 *Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017* (Oslo: Arctic Monitoring and Assessment Programme (AMAP))
- Ask A and Routti H 2017 Terrestrial permafrost areas—the state of knowledge on transport, fate and degradation of halogenated organic compounds Brief Report No. 043 (Oslo: Norwegian Polar Institute)
- Bhatt U S, Walker D A, Reynolds M K, Bieniek P A, Epstein H E, Comiso J C, Pinzon J E, Tucker C J and Polyakov I V 2013 Recent declines in warming and vegetation greening trends over pan-Arctic tundra *Remote Sens.* **5** 4229–54
- Bjerke J W, Karlsen S R, Høgda K A, Malnes E, Jepsen J U, Lovibond S, Vikhamar-Schuler D and Tømmervik H 2014 Record-low primary productivity and high plant damage in the Nordic Arctic Region in 2012 caused by multiple weather events and pest outbreaks *Environ. Res. Lett.* **9** 084006
- Bjerke J, Treharne R, Vikhamar-Schuler D, Karlsen S, Ravolainen V, Bokhorst S, Phoenix G, Bochenek Z and Tømmervik H 2017 Understanding the drivers of extensive plant damage in boreal and Arctic ecosystems: insights from field surveys in the aftermath of damage *Sci. Total Environ.* **599–600** 1965–76
- Bjorkman A D *et al* 2018 Plant functional trait change across a warming tundra biome *Nature* **562** 57–62
- Blok D, Sass-Klaassen U, Schaepman-Strub G, Heijmans M M P D, Sauren P and Berendse F 2011 What are the main climate drivers for shrub growth in Northeastern Siberian tundra? *Biogeosciences* **8** 1169–79
- Bokhorst S E, Bjerke J W, Tømmervik H, Callaghan T V and Phoenix G K 2009 Winter warming events damage sub-Arctic vegetation: consistent evidence from an

- experimental manipulation and a natural event *J. Ecol.* **97** 1408–15
- Buchwal A, Rachlewicz G, Fonti P, Cherubini P and Gärtner H 2013 Temperature modulates intra-plant growth of *Salix polaris* from a High Arctic site (Svalbard) *Polar Biol.* **36** 1305–18
- Buchwal A, Weijers S, Blok D and Elberling B 2019 Temperature sensitivity of willow dwarf shrub growth from two distinct High Arctic sites *Int. J. Biometeorol.* **63** 167–81
- Büntgen U, Hellmann L, Tegel W, Normand S, Myer-Smith I H, Kirilyanov A, Nievergelt D and Schweingruber F H 2015 Temperature driven germination pulse of Arctic dwarf shrub communities *J. Ecol.* **103** 489–501
- Callaghan T V and Tweedie C E (eds) 2011 Multi-decadal changes in tundra environments and ecosystems: the International Polar Year back to the future project *AMBIO* **40** 555–692
- Christiansen H H, Etzelmüller B, Isaksen K, Juliussen H, Farbrot H, Humlum O and Ødegård R S 2010 The thermal state of permafrost in the Nordic area during the International Polar Year 2007–2009 *Permafrost. Periglac. Process.* **21** 156–81
- Cooper E J, Little C J, Pilsbacher A K and Mörsdorf M A 2019 Disappearing green: shrubs decline and bryophytes increase with nine years of increased snow accumulation in the High Arctic *J. Veg. Sci.* **30** 857–67
- eKlima 2019 Weather- and climate data from Norwegian Meteorological Institute (available at: <http://eklima.met.no>) (Accessed March 2019)
- Elmendorf S et al 2012 Plot-scale evidence of tundra vegetation change and links to recent summer warming *Nat. Clim. Change* **2** 453–7
- Elvebakk A 1985 Higher phytosociological syntaxa on and their use in the subdivision of the Arctic *Nord. J. Bot.* **5** 273–84
- Elvebakk A 1994 A survey of plant associations and alliances from Svalbard *J. Veg. Sci.* **5** 791–802
- Engelskjøn T 1986 Eco-geographical relations of the Bjørnøya vascular flora, Svalbard *Polar Res.* **5** 79–127
- Engelskjøn T and Schweitzer H J 1970 Studies on the flora of Bear Island (Bjørnøya). I. Vascular plants *Astarte* **3** 1–36
- Epstein H E, Bhatt U S, Reynolds M K, Walker D A, Forbes B C, Macias-Fauria M, Lorant M, Phoenix G and Bjerke J 2017 Tundra greenness in state of the climate in 2016 *Bull. Am. Meteorol. Soc.* **98** 145–7
- Forbes B C, Fauria M and Zetterberg P 2010 Russian Arctic warming and 'greening' are closely tracked by tundra shrub willows *Glob. Change Biol.* **16** 1542–54
- Forchhammer M 2017 Sea-ice induced growth decline in Arctic shrubs *Biol. Lett.* **13** 20170122
- Førland E J and Hanssen-Bauer I 2000 Increased precipitation in the Norwegian Arctic: true or false? *Clim. Change* **46** 485–509
- Frost G V and Epstein H E 2014 Tall shrub and tree expansion in Siberian tundra ecotones since the 1960s *Glob. Change Biol.* **20** 1264–77
- Gärtner H and Schweingruber F H 2013 *Microscopic Preparation Techniques for Plant Stem Analysis* (Remagen-Oberwinter: Verlag Dr. Kessel)
- Grime J P 1979 *Plant Strategies and Vegetation Processes* (Hoboken, NJ: Wiley)
- Hallinger M, Manthey M and Wilmking M 2010 Establishing a missing link: warm summers and winter snow cover promote shrub expansion into alpine tundra in Scandinavia *New Phytol.* **186** 890–9
- Holmes R J 1983 Computer-assisted quality control in tree-ring dating and measurement *Tree-Ring Bull.* **43** 69–78
- Horn G and Orvin A K 1928 Geology of Bear Island *Skrifter Om Svalbard Og Ishavet* **15** 152
- Jia G J, Epstein H E and Walker D A 2003 Greening of arctic Alaska, 1981–2001 *Geophys. Res. Lett.* **30** 2067
- Kolishchuk V et al 1990 Dendroclimatological study of prostrate woody plants *Methods of Dendrochronology: Applications in the Environmental Sciences*, ed E Cook (London: Kluwer) 51–5
- Lara M J, Nitze I, Grosse G, Martin P and Mcguire A D 2018 Reduced arctic tundra productivity linked with landform and climate change interactions *Sci. Rep.* **8** 2345
- Le Moullec M, Buchwal A, Wal R, Sandal L and Hansen B B 2019 Annual ring growth of a widespread high arctic shrub reflects past fluctuations in community-level plant biomass *J. Ecol.* **107** 436–51
- Macias-Fauria M, Forbes B C, Zetterberg P and Kumpula T 2012 Eurasian Arctic greening reveals teleconnections and the potential for structurally novel ecosystems *Nat. Clim. Change* **2** 613–8
- Macias-Fauria M, Karlsen S R and Forbes B C 2017 Disentangling the coupling between sea ice and tundra productivity in Svalbard *Sci. Rep.* **7** 8586
- Martin A C, Jeffers E S, Petrokofsky G, Myers-Smith I and Macias-Fauria M 2017 Shrub growth and expansion in the Arctic tundra: an assessment of controlling factors using an evidence-based approach *Environ. Res. Lett.* **12** 085007
- Myers-Smith I H et al 2011 Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities *Environ. Res. Lett.* **6** 045509
- Myers-Smith I H et al 2015a Climate sensitivity of shrub growth across the tundra biome *Nat. Clim. Change* **5** 887–91
- Myers-Smith I H et al 2015b Methods for measuring arctic and alpine shrub growth: a review *Earth Sci. Rev.* **140** 1–13
- Myers-Smith I H et al 2020 Complexity revealed in the greening of the Arctic *Nat. Clim. Change* **10** 106–17
- Opala-Owczarek M, Owczarek P, Łupikasza E, Boudreau S and Migala K 2020 Influence of climatic conditions on growth rings of *Salix uva-ursi* Pursh from the South-Eastern Shore of Hudson Bay, subarctic Canada *Arct. Antarct. Alp. Res.* **52** 87–102
- Opala-Owczarek M, Pirożnikow E, Owczarek P, Szymański W, Luks B, Kępski D, Szymanowski M, Wojtun B and Migala K 2018 The influence of abiotic factors on the growth of two vascular plant species (*Saxifraga oppositifolia* and *Salix polaris*) in the High Arctic *Catena* **163** 219–32
- Owczarek P 2010 Dendrochronological dating of geomorphic processes in the High Arctic *Landf. Anal.* **14** 45–56
- Owczarek P, Latocha A, Wistuba M and Malik I 2013 Reconstruction of modern debris flow activity in the arctic environment with the use of dwarf shrubs (south-western Spitsbergen)—a new dendrochronological approach *Z. Geomorphol. Suppl.* **57** 75–95
- Owczarek P, Nawrot A, Migala K, Malik I and Korabiewski B 2014 Flood-plain responses to contemporary climate change in small High-Arctic basins (Svalbard, Norway) *Boreas* **43** 384–402
- Owczarek P and Opala M 2016 Dendrochronology and extreme pointer years in the tree-ring record (AD 1951–2011) of polar willow from southwestern Spitsbergen (Svalbard, Norway) *Geochronometria* **43** 84–95
- Peeters B, Pedersen Å Ø, Loe L E, Isaksen K, Veiberg V, Stien A, Kohler J, Gallet J-C, Aanes R and Hansen B B 2019 Spatiotemporal patterns of rain-on-snow and basal ice in high Arctic Svalbard: detection of a climate-cryosphere regime shift *Environ. Res. Lett.* **14** 015002
- Phoenix G K and Bjerke J W 2016 Arctic browning: extreme events and trends reversing arctic greening *Glob. Change Biol.* **22** 2960–2
- Przybylak R 2016 *The Climate of the Arctic* (Berlin: Springer)
- Raynolds M K, Comiso J C, Walker D A and Verbyla D 2008 Relationship between satellite-derived land surface temperatures, Arctic vegetation types, and NDVI *Remote Sens. Environ.* **112** 1884–94
- Reichle L M, Epstein H E, Bhatt U S, Reynolds M K and Walker D A 2018 Spatial heterogeneity of the temporal dynamics of Arctic tundra vegetation *Geophys. Res. Lett.* **45** 9206–15
- Rønning O I 1996 *The Flora of Svalbard* (Oslo: Norwegian Polar Institute)

- Schmidt N, Baittinger C and Forchhammer M 2006 Reconstructing century-long snow regimes using estimates of High Arctic *Salix arctica* radial growth *Arct. Antarct. Alp. Res.* **38** 257–62
- Schweingruber F H and Poschold P 2005 *Growth Rings in Herbs and Shrubs: Life Span, Age Determination and Stem Anatomy* vol 79 (Bern: Haupt Forest Snow and Landscape Research)
- Theisen F 1997 *Dokumentasjon Og Vurdering Av Verneverdier På Bjørnøya* vol 143 (Oslo: Norsk Polarinstitutt, Meddelelser)
- Tømmervik H and Forbes B C 2020 Focus on recent, present and future Arctic and boreal productivity and biomass changes *Environ. Res. Lett.* **15** 080201
- Van der Wal R and Stien A 2014 High-arctic plants like it hot: a long-term investigation of between-year variability in plant biomass *Ecology* **95** 3414–27
- Vickers H, Høgda K A, Solbø S, Karlsen S R, Tømmervik H, Aanes R and Hansen B B 2016 Changes in greening in the high Arctic: insights from a 30 year AVHRR max NDVI dataset for Svalbard *Environ. Res. Lett.* **11** 105004
- Vikhamar-Schuler D, Isaksen K, Haugen J E, Tømmervik H, Luks B, Schuler T V and Bjerke J W 2016 Changes in Winter warming events in the Nordic Arctic Region *J. Clim.* **29** 6223–44
- Walczowski W, Piechura J, Goszczko I and Wieczorek P 2012 Changes in Atlantic water properties: an important factor in the European Arctic marine climate *ICES J. Mar. Sci.* **69** 864–9
- Weijers S, Broekman R and Rozema J 2010 Dendrochronology in the High Arctic: July air temperatures reconstructed from annual shoot length growth of the circumarctic dwarf shrub *Cassiope tetragona* *Quat. Sci. Rev.* **29** 3831–42
- Weijers S, Buchwal A, Blok D, Löffler J and Elberling B 2017 High Arctic summer warming tracked by increased *Cassiope tetragona* growth in the world's northernmost polar desert *Glob. Change Biol.* **23** 5006–20
- Weijers S, Pape R, Löffler J and Myers-Smith I H 2018 Contrasting shrub species respond to early summer temperatures leading to correspondence of shrub growth patterns *Environ. Res. Lett.* **13** 034005
- Wolf A, Larsson K and Callaghan T V 2008 Future vegetation changes in the Barents Region *Clim. Change* **87** 51–73
- Worsley D, Agdestein T, Gjelberg J G, Kirkemo K, Mørk A, Nilsson I, Olaussen S, Steel R J and Stemmerik L 2001 The geological evolution of Bjørnøya, Arctic Norway: implications for the Barents Shelf *Norsk Geol. Tidsskr.* **81** 195–234
- Young A B, Watts D A, Taylor D A and Post E 2016 Species and site differences influence climate-shrub growth responses in West Greenland *Dendrochronologia* **37** 69–78
- Zalatan R and Gajewski K 2006 Dendrochronological potential of *Salix alaxensis* from the Kuujua river area, Western Canadian Arctic *Tree-Ring Res.* **62** 75–82
- Żmudczyńska-Skarbek K, Barcikowski M, Drobniak S M, Gwiazdowicz D J, Richard P, Skubała P and Stempniewicz L 2017 Transfer of ornithogenic influence through different trophic levels of the Arctic terrestrial ecosystem of Bjørnøya (Bear Island), Svalbard *Soil Biol. Biochem.* **115** 475–89
- Zwolicki A, Żmudczyńska-Skarbek K, Richard P and Stempniewicz L 2016 Importance of marine-derived nutrients supplied by planktivorous seabirds to High Arctic tundra plant communities *PloS One* **11** e0154950