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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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Abstract
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.

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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, Tommervik 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 Moullac et al 2019, Opala-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, Opala-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, Opala-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, Opala-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 Miseryfiellet (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 Miseryfiellet and Skrekjøvet 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 $-5.43 \degree C$ (in 1969) to $1.81 \degree C$ (in 2016), averaging $-1.39 \degree C$ (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 $-0.29 \degree C$ per decade, whereas in 1976–2000 these trends have already reached $+0.49 \degree C$ per decade. Since the beginning of the 21st century, increases in temperature have accelerated, equalling $1.09 \degree C$ (2000–18), similar to the early period of observations, 1922–40 (0.73 $\degree C$ per decade). The annual total precipitation in this area is 396.4 mm 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 $-6.41 \degree C$, and the warmest is August, with an average temperature of 4.97 $\degree C$ (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 (Phippsia 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, Zmudzyńska-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)).
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 Miseryfjellet 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 µm) to extremely narrow (less than 10 µm). 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 use 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.
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 $\mu$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 $\mu$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 $\mu$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 $\mu$m. Since the 1980s absolute growth increment rates variability have been increasing. Absolute growth rates ranged from 17.01 to 61.56 $\mu$m in the years 1980–2005. After 2005 the absolute growth decreased and ranged from 25.72 to 30.38 $\mu$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 Opała 2016, Forchhammer 2017, Opała-Owczarek et al 2018). Attempts to use Arctic dendrochronology as a tool for climate reconstruction are limited by the age of tundra plants.
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 Opala (2016), who confirmed that the age of an
S. polaris specimen may exceed 105 years. In the present study, using serial sec-
tioning 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 fur-
ther 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,
Weiwers 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 sea-
son, 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 (Opala-Owczarek et al 2018). The
impact of drought on tundra vegetation is deter-
mined 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.

The increase in the frequency of winter thaws after
2000 has also caused significant changes in the snow-

ness 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 ini-
tial growing season. Progressive warming and insuf-
ficient amounts of spring meltwater result in higher
sensitivity of annual growth rate of S. polaris to pre-
cipitation (figure 8). This relationship can be con-
irmed by the previous report of Opala-Owczarek
et al (2018). In warmer and faster thawing perma-
frost, 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 Opala 2016, Opala-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
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 char-
acterised 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 pro-
cesses 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 Sval-
bard 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 (Macías-Fauría 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 Opala 2016, Opla-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 (Osl: Norwegian Polar Institute)


Björkman A D et al 2018 Plant functional trait change across a warming tundra biome Nature 562 57–62


Bokhorst S F, 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
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
Cooper E J, Little C J, Bilsbacher 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
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. 7 791–802
Engelksén T 1986 Eco-geographical relations of the Björnøya vascular flora, Svalbard Polar Res. 5 79–127
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
Gätter H and Schweingruber F H 2013 Microscopic Preparation Techniques for Plant Stem Analysis (Remagen-Oberwinter: Verlag Dr. Kessel)
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 Geography of Bear Island Skrifter Om Svalbard Og Isfjord 15 152
Lara M J, Nitze I, Grosse G, Martin P and Muguire A D 2018 Reduced arctic tundra productivity linked with landform and climate change interactions Sci. Rep. 8 2345
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
Myers-Smith I H et al 2011 Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities Environ. Res. Lett. 6 045509
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 Geomorphol. Suppl. 57 75–95
Przybylak R 2016 The Climate of the Arctic (Berlin: Springer)
Rönnö O I 1996 The Flora of Svalbard (Oslo: Norwegian Polar Institute)
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)
Theise n F 1997 Dokumentasjon Og Vurdering Av Verneverdier På Bjørnøya vol 143 (Oslo: Norsk P o larinst ut, 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
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, 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
Zalatan R and Gajewski K 2006 Dendrochronological potential of Salix alaxensis from the Kuujjua river area, Western Canadian Arctic Tree-Ring Res. 62 75–82
Zmudczyńska-Skarbek K, Barci kowski M, Drobnia k 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