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EXECUTIVE SUMMARY

This project report summarizes and discusses the impacts of ongoing and future climate change on ecosystems, major industries, and indigenous livelihoods in the European Arctic, including Greenland. The industries in focus are fish farming (i.e., aquaculture), forestry, mining, and tourism. Focus is given to the 17 main study areas of the ArcticHubs project. These study areas are called "hubs" and are distributed in northern Finland (4 hubs), northern Sweden (3), Norway (4), Iceland (1), Faroe Islands (1), Greenland (1), and north-western Russia (2).

The report relies on a combination of new data analyses, including climate projections, and a summary of knowledge from the vast amount of primary and secondary literature covering the study areas or adjacent areas with similar climate, ecosystems, and human activity. In this context, "primary" refers to scientific peer-reviewed research literature, while "secondary" refers to reviews or summaries at variable geographical scales – from regional (intra-country) to global. As land use change and climate change can result in similar ecosystem responses, this report elaborates on the distinction between various anthropogenic forces. The summary of the state-of-the-art is supported by analyses of recent remotely sensed changes of vegetation greenness for specific hubs, and climate projections retrieved from the CMIP6 ECEarth3 (Earth System Model) data downscaled to hub level.

Climate has changed in the whole study area during the Anthropocene and more rapidly so than at lower latitudes; while the annually averaged global near-surface air temperature increased by 1.0 °C from 1971 to 2019, the boreal-Arctic (> 60° N) near-surface air temperature increased by 3.1°C. The general trend is that winters have been warming more than summers. Still, some recent extremely warm summers have led to drought in parts of the study area. Sea temperature has also increased in northern Europe, resulting in reduced sea ice extent in major oceans (Arctic Ocean, Atlantic Ocean, Barents Sea) and in closed bodies of ocean (for example Norwegian fjords, Bothnia Bay, White Sea).

Warming on land has also had major impact on the cryosphere: snow seasons have become shorter and wetter, snowpacks shallower and with higher density of refreezing icy layers, growing season start has advanced, the snow-free period in autumn has prolonged, and alpine and Greenlandic glaciers are retreating rapidly. Numerous regions previously characterized by a stable winter climate, have experienced high frequency of thaw weather (i.e., increasing number of days per winter with temperature above 0 °C) and unstable snow conditions.

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Climate has changed more rapidly in the northernmost hubs, especially on Svalbard where the northernmost parts of the archipelago where the near-surface air temperature in the northernmost parts of the archipelago increased by 8 °C from 1971 to 2019.

In this report, scenarios at hub-level relying on the Coupled Model Intercomparison Project Phase 6 Shared Socioeconomic Pathway 5 (SSP5) are shown. These climate projections show that drastic changes will occur in all hubs towards the end of the 21st Century. The entire study region will become warmer and wetter in all seasons, while snow accumulation will be drastically reduced. The high-latitude hubs will change more than the hubs and learning cases at lower latitudes.

Ecosystems are changing rapidly from a combination of land use changes and climate change. The most rapid changes in species distribution occur in marine waters. Gradual climate change and increased frequency of extreme weather events have contrasting effects on ecosystems. For predictions of future ecosystem change, these two elements of climate change must both be considered.

Nature-based industries and indigenous activities will need to drastically adapt to the ongoing rapid climatic changes. Arctic communities are facing highly challenging changes to their environment. Reindeer husbandry in Finland, Norway and Sweden is already experiencing the dramatic impacts of climate change. Shorter snow seasons, increasing frequency of ice layers in the snowpack, and unsafe lake and river ice are only some of the winter-related changes that have negative consequences for reindeer husbandry. Extreme heat, increasing insect harassment, parasitic epidemics and new invasive alien insects are examples of changes that lead to more challenging summer periods. Traditional Greenlandic hunting and fishing are also changing due to warming marine waters, shorter sea ice season, and declining populations of animals hunted for food and materials.

The future magnitude of tourists to northern regions will be a result of non-climatic global drivers and climatic change. The risk of reduced snow amounts, increased cloudiness and increased rainfall in winter may affect winter tourism negatively both through their impacts on traditional snow activities and their impacts on northern lights watching, which can become harder to spot due to increasing cloudiness. On the other hand, last-chance tourism, which involves watching of the arctic environment with glaciers, snow-capped mountains, and arctic animals before it becomes a rare phenomenon, may increase in popularity. Escaping from summer heat tourism will probably also lead to increasing northward expansion of tourist masses. Arctic tourist destinations are under increasing pressure from tourism. There are signs

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of overtourism effects on some arctic destinations, and indicators of overtourism will increase if last-chance and heat-escape tourism will continue to expand into northern regions.

Warmer and longer growing seasons have the potential to stimulate to more rapid tree growth, and hence improve the economy in northern forestry. On the other hand, Nordic commercial tree species are adapted to cool summers and cold winters. The rapid climate change will therefore impose increasing climatic and biotic stress to trees both during the growing season and during the hibernation period. The total impact on the economy in forestry is therefore uncertain.

The projected climate change will have direct and indirect effects on the Faroese, Icelandic and Norwegian fish farming hubs. Rising seawater temperatures will directly affect the conditions for farming of the cold-water fish species such as Atlantic salmon, which is the economically most important species in these hubs. Future projected increase in seawater temperature will be problematic for the Egersund hub, where summer seawater temperature will likely exceed optimal thermal limits for growth of Atlantic salmon during periods. Higher seawater temperatures are going to also exacerbate disease and parasite dynamics in the south, probably leading to northwards shift favouring fish farming hubs in the north.

There is an enormous economic potential in northern bedrock for mineral exploration of critical raw materials. Retreating glaciers and declining sea ice extent lead to large new areas are becoming available for exploration. Within the study region, increasing hazards related to permafrost thaw are restricted to Greenland and Svalbard. Soil instability and changes in hydrology can result in damage to infrastructure, increasing weathering of installations, and increased leakage of pollutants.

Overall, this study combining extensive reviews of published material and new data analyses, provide unanimous evidence that climate change will have massive effects on nature and nature-based industries and arctic livelihoods. Wide-range impacts of climate change on nature and society are already evident, even if it not always possible to differentiate between the relative weight over various drivers of change. For example, human land use, harvesting and pollution have led to massive changes to nature. However, during the 21st Century the impact of climate change will become the primary driver of changes to nature, and hence, to nature-based industries. In some cases, climate change will stimulate economic growth, while in other cases, it will have negative effects on indigenous livelihoods and nature-based industries.

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1 Introduction

Global climate is under rapid change; the last seven years (2015-21) were the seven warmest years on record [26]. Northern latitudes, i.e., areas poleward of 60° N, are warming more than the global average. In 2020, the annual mean surface air temperature anomaly for terrestrial areas poleward of 60° N was 2.1 °C above the 1981–2010 average; continuing a pattern of seven consecutive years where surface air temperature anomalies were more than 1 °C higher than the 1981–2010 average [27]. While the annually averaged global near-surface air temperature (land and sea) increased by 1.0 °C from 1971 to 2019, the northern latitudes' near-surface air temperature increased by 3.1°C [28]. Year 2021 was the coolest year in the Arctic since 2013, but still the 13th-warmest year on record (since 1900) [29].

The northern warming amplification has also led to a 43 % decline (1979-2019) in Arctic sea-ice extent and increasing sea surface temperature [30]. Surface waters in August in the North Atlantic region – from the west coast of Greenland to the Barents Sea – have been warming between 0.05 and 0.1 °C per year from 1982 to 2020. This is associated with an annual decline of 1.31 % of sea ice extent (measured in the month when the minimum sea ice extent occurs), relative to the 1981-2010 average [31]. Declining sea ice results in higher-than-average warming trends of nearby land areas due to positive feedback loops. Over longer time scales, trends in sea surface temperature in the North Atlantic region differ between regions, generally with strong warming in the east, whereas the waters southeast of Greenland have experienced only weak warming, or even slight cooling over some decadal intervals [32]. On shorter time scales, natural variations are superimposed on the anthropogenic warming as documented for various locations by the International Council for the Exploration of the Sea [33].

The study area in the ArcticHubs project has a wide geographical range. Longitudinally, it includes study sites from the western coast of Greenland to the Kola Peninsula, while latitudinally it includes truly Arctic sites such as Svalbard and Greenland and forest-and-alpine sites in northern Italy (Figure 1.1).

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[26] Dunn et al. 2022
[27] Druckenmiller et al. 2021
[28] Arctic Monitoring and Assessment Programme 2021, Box et al. 2022
[29] Thoman et al. 2022
[30] Box et al. 2022
[31] Meier et al 2021
[32] Lavoie et al. 2013, 2019
[33] González-Pola et al. 2020

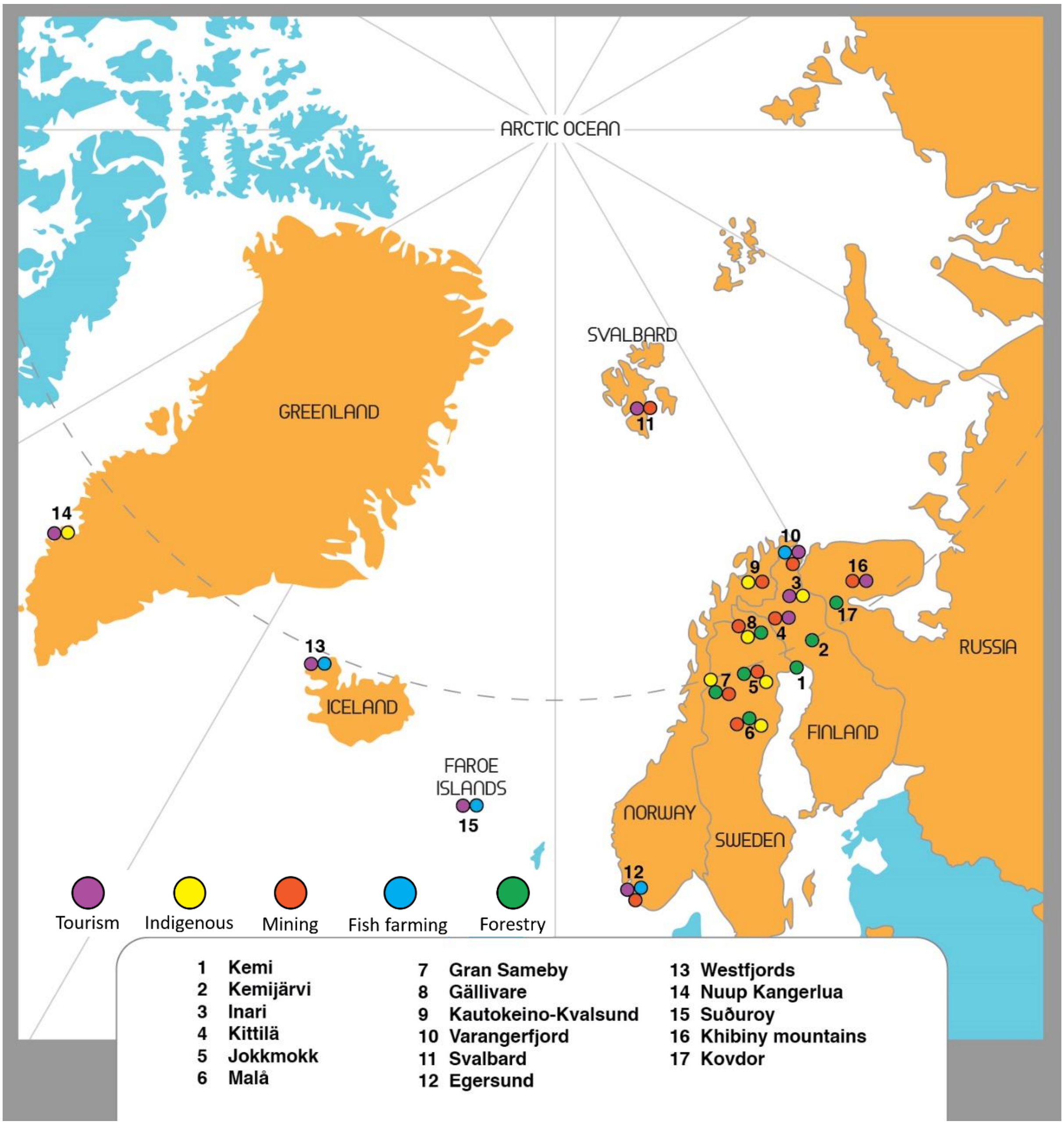

Figure 1.1. Locations of hubs and learning cases targeted in ArcticHubs. Orange indicates countries with consortium members. Numbers in the map refer to the locations of the 17 hubs [34]. Dot colours refer to target activities within each hub. Purple: tourism; yellow: indigenous; red: mining; blue: fish farming; green: forestry.

There are seasonal differences in warming rate. Within the ArcticHubs' study area, the autumn, winter and spring seasons are warming more rapidly than the summer season [35]. Warming in these three seasons is most pronounced at the northernmost hub Svalbard and the two

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[34] The map does not show the learning cases in Italy, Austria and Canada. Learning cases in Italy and Austria and hubs in Russia (16 and 17) were reflected on but are only briefly covered in this report.

[35] You et al. 2021

westernmost hubs Nuup Kangerlua (Greenland) and Westfjords (Iceland). These warming trends will continue during the rest of this century. However, the warming rate will depend on the climate mitigation efforts.

This project report responds to Task 2.2. *Analysis of the impact of climate change on Arctic terrestrial and marine ecosystems*. The main research question addressed in the project report is: What are the main ecosystem responses to recent climate change in the Arctic target hubs and which further ecosystem changes are expected during the course of the 21st century?

By responses, we mean detectable changes in terrestrial and marine ecosystems, or parts of ecosystems (e.g., changes in keystone and threatened species or major habitat types), that are attributable to climatic change, either gradual or sudden change. While gradual climate change generally leads to gradual changes in the distribution and abundance of a species, abrupt ecological change may be the result of sudden changes in forcing agents or the effects of gradual or stochastic changes that, either acting periodically or together, exceed some critical threshold or "tipping point" [36]. Very rapid trend-based climatic change or increasing frequency of anomalous weather events because of climatic change, are examples of forcing agents that can cause abrupt ecological change.

While this project report has focus on all ecosystems and living organisms on land, in freshwater and in sea, particular attention is given to ecosystems and species that are important for indigenous peoples and local economies relying on harvesting of biological resources. This is applicable especially (but not exclusively) for those related to the main themes of ArcticHubs, namely fish farming, forestry, mining and indigenous issues (Figure 1.1). Possible consequences of climate-induced ecosystem change on tourism is also discussed in this report.

In the next section of the report, data and methods are described. Thereafter follow sections on recent and future elements of climatic change; recent and future ecosystem change on land and in sea; and consequences of climatic change on economic activities in the Arctic, with particular focus on the project's hubs (Figure 1.1). Analyses of the relative importance of climate vs. land use change for the observed (historic) and modelled (future) ecosystem changes are also provided. Concluding remarks are provided at the end of the report.

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[36] Harley and Paine 2009

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2 Data and method

This study is an analysis partly of existing information published in scientific and policy reports and partly relying on oral reports from people working in the field such as Sami reindeer herders, hunters and fishermen, and partly based on new, hitherto unpublished, quantitative analyses undertaken particularly for this report. It is a product of Task 2.2 ("Analysis of the impact of climate change on Arctic terrestrial and marine ecosystems") of the ArcticHubs project [37]. Data were compiled by project research partners from several fields of science with expert knowledge on the project's many hubs. Thus, the dataset retrieved from published sources includes results from primary studies published in international scientific journals, summaries from global or other intercontinental reports (such as reports from the Intergovernmental Panel on Climate Change and the annual reports on the State of the Climate from the National Oceanic and Atmospheric Administration), and reports on more regional scales, including reports on national level and in various languages.

The report is ordered according to theme (physical part, biological part) and scale, i.e., from impacts or trends nearly identical for the entire study area to impacts or trends evidently restricted to hub level. Various essential variables of climate change were considered.

This includes changes to seasonal and annual temperature and precipitation at land and in oceans, state of precipitation (i.e., rain vs. snow), length of seasons, and onset of growing season. The literature review is complemented with novel, previously unpublished, analyses, which are described here.

Recent (2000-2021) remotely sensed changes of vegetation greenness at regional and hub level are presented in sections 3.1.2 and 4.1.1, using the methodology described in Høgda et al. and Karlsen et al. [38]. Two global data series of satellite data were processed for various Normalized Difference Vegetation Index (NDVI) outputs. The first is GIMMS NDVI [39] from year 1982-

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[37] Full description of Task 2.2 as stated in the project description: *Task 2.2 will gain understanding of the past and present ecosystem states by analysing long-term data sets and collecting new data, and by comparing these datasets with meteorological data. Phenology and productivity trends and regional changes in state and composition of vegetation will be analysed in relation to climatic data (both trends and extremes), using both field and remotely sensed vegetation data. Relying on climate projections for the next 80 years, task 2.2. will apply modelling approaches to assess future states of marine and terrestrial environments based on climatic change only, and this will feed into tasks 2.3 and 2.4 as one of the main drivers of change. For the Arctic marine environment, the key questions related to changes in climate are: what are the key characteristics of past temporal and spatial variations in fish and benthos ecosystem, and how are these related to past climate variability and fishing pressure. The objective is to evaluate the effects of global environmental changes on the future structure of the marine ecosystem in Arctic under particular environmental and fisheries scenarios.*

[38] Høgda et al. 2013, Karlsen et al. 2018

[39] Global Inventory Modelling and Mapping Studies (GIMMS)

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2020. Furthermore, MODIS NDVI [40] was processed for the period 2000-2021 based on MODIS version 6.0. Several parameters related to the growing season were computed and analysed. This includes the yearly maximum (peak) NDVI (MaxNDVI), time of start of growing season, time of end of growing season, length of growing season, and summed NDVI (SumNDVI) and the time-integrated NDVI from onset of growth to time of peak (OP NDVI). For Svalbard, a new cloud-free MODIS dataset interpolated to daily data, with 231.65 m pixel resolution for the 2000-2021 period covering the entire archipelago have been processed. From this dataset several growing seasonal parameters, as mentioned above, were extracted.

Satellite data from Iceland used in this study was acquired from NASA's Land Processes Distributed Active Archive Center (LP DAAC) collections from 2022 and consists of 22 years of NDVI images at monthly intervals from the vegetation index dataset- MOD13A3 V6. Specifically, the Applications for Extracting and Exploring Analysis Ready Samples (AppEEARS) was used to download all NDVI imagery from 2000 to 2021, projected in Sinusoidal Projection [41]. The spatial resolution is 1 km, and the spectral resolution is 0.6-1.1 µm, e.g., the red and the NIR spectrum. The satellite data is collected by the MODIS-sensor aboard NASA's spacecraft Terra. In addition to the NDVI images, the download request also included Enhanced Vegetation Index (EVI), vegetation index quality, and pixel reliability layers for reference.

Hub-level data were retrieved from a coordinate located in the centre of each hub, with the assumption that this point is representative for the entire hub. Around this centre point, 5 × 5 GIMMS pixels were analysed, each analysis representing 1600 km^2 [42]. We also extracted MODIS-data for the same area. A total area-based analysis of each hub would have required much more data processing requirements. Moreover, as none of the hubs have exact geographical delimitations, it would be risking the inclusion of areas that are not particularly relevant for the hubs. Therefore, it was decided that a central point would suffice for this analysis.

The same coordinates were applied in the projections of future climate change at hub level. Data at monthly scales were retrieved from the CMIP6 ECEarth3 data [43]. These projections are central for the treatment of hub-specific projections of climate change until year 2100.

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[40] Moderate-resolution Imaging Spectroradiometer (MODIS)
[41] Didan 2015, AppEEARS Team 2022
[42] Note: a GIMMS pixel is 8 km × 8 km. (8 × 8) × (5 ×5) = 1600.
[43] O'Neill et al. 2016

The data are discussed and analysed by the research partners from the various hubs and with expertise in various focal topics of the project (forestry, fish farming, mining, indigenous issues), after which each partner provided textual or other contributions to the report. Lead authors compiled the text, and after proofreading, the co-authors had a second opportunity to check the entire report, or parts of it, depending on their available time and expertise. Hence, this project report is a collaborative effort of scientists conducting studies in various fields of science.

Figure 2.1. Forestry is one of the core activities covered in this report. This is from a production Scots pine forest near the Varangerfjorden hub. Photo: Jarle W. Bjerke ©

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3 Climate change in the European Arctic: recent trends and pulses, and projections until 2100

While boreal and Arctic climate has changed rapidly during the last 30 years (Sections 3.1-3.2), this change is expected to be minor compared to the forecasted changes during the remainder of the 21st century. The rate of future change will depend on the global effort to halt climatic change through mitigation measures (Section 3.3). Regardless of mitigation efforts, the ongoing changes will cause major ecosystem change (Chapter 4) and entail radical adaptiveness within northern societies and industries [44]. Societal and industrial consequences is further reviewed and discussed in Chapter 5.

In this chapter, we document and discuss the physical evidence of recent and future climate change with particular focus of the ArcticHubs study region (Figure 1.1).

3.1 Observations of long-term gradual trends (ca. 1951-2021)

Globally, each of the last four decades has been successively warmer than any preceding decade since 1850 [45]. Warming has been most pronounced poleward of 60° N, particularly over Arctic seas and associated islands and archipelagos (e.g., Svalbard, Novaya Zemlya, Banks Island, and the north-eastern part of Greenland), but also over the northern stretches of the North American and Siberian continental landmasses [46].

3.1.1 Annual temperature and precipitation

For the most recent 5-year period (2017-2021), the annual temperature of all hubs but one (Figure 1.1) was 1-4 °C warmer than the base period 1951-1970 [47]. The only exception is Nuup Kangerlua, which was 0.5-1.0 °C warmer than the base period, as also confirmed in a study specifically focussing on this hub [48]. For the ArcticHubs study region, the annual warming trend since 1971 is most pronounced for Svalbard, in particular the eastern half of the archipelago, which has warmed by more than 4.0 °C during this period. The mainland hubs of northern Norway, northern Finland, northern Sweden, and Kola Peninsula (hub numbers 1-10 and 16-17) follow thereafter with a 2.0-4.0 °C temperature increase. The learning cases in Italy and

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[44] Hovelsrud et al. 2011, Ford et al. 2021
[45] IPCC 2021
[46] NASA 2022
[47] Temperature maps retrieved from NASA 2022. Note: Comparison of annual temperature of 2011-2021 and 2017-2021 against the base period 1951-1970, and trends for 1971-2021.
[48] López-Blanco et al. 2017

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Austria have also experienced a pronounced warming between 2.0-4.0 °C. The remaining hubs have had an annual temperature increase of 1.0-2.0 °C since 1971.

The project's Atlantic hubs on The Faroe Islands and Iceland are surrounded by ocean on all sides. Historical figures since 1873 show a clear trend of temperature increase in the Faroe Islands [49]. For this hub, the future development in temperature will critically depend on the temperature development of the surrounding ocean and potential changes in ocean currents, which are part of the Atlantic Meridional Overturning Circulation (AMOC) [50].

A warmer atmosphere can hold more water vapour. Thus, the recent warming has been associated with increasing precipitation rates at high northern latitudes. Specific humidity and precipitation have increased at high northern latitudes [51]. This is also evident from long-term precipitation records from the ArcticHubs study region. For example, the hubs Kvalsund-Kautokeino and Varangerfjord in northernmost mainland Norway have had a significant annual precipitation increase of 1.6 % per decade (data period 1900-2014) [52]. The same trend is evident within the Swedish study area of this project; the yearly normal for precipitation increased by 12.3 % (± 4.9 % SD) from the 1961-1990 normal to the 1991-2020 normal for weather stations north or 64° N [53]. Analyses of a much longer time series, from 1902 to 2018, also show that northern Sweden has become significantly wetter in all seasons [54], while 55 homogeneity-tested stations distributed throughout Norway reveal a 19 % increase in precipitation from 1900 to 2019, during which the steepest increase took place between 1995 and 2015 [55].

In the Faroe Islands, large variation in precipitation is seen over the period from 1890 to 2020, masking any significant trend changes [56]. Our own analyses, based on available Greenland meteorological data [57], show that the Nuuk area has experienced an increase of only 5.2 % in precipitation from the period 1958-1968 to the period 2004-2013, while its variability increased significantly ($SD_{1958-1968} = 172$ mm vs $SD_{2004-2013} = 630$ mm).

Caution should be taken when interpreting time series from rain gauges. Wind and turbulence may in some cases lead to a severe underestimation of actual precipitation of up to 60 %,

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[49] Cappelen 2021
[50] IPCC 2021
[51] Prowse et al. 2017
[52] Hanssen-Bauer et al. 2015
[53] Data source: Swedish Meteorological and Hydrological Institute 2022a. Note: our own analyses for this report based on the comparison of precipitation normals for 1961-1990 vs. 1991-2020.
[54] Chen et al. 2020
[55] Konstali & Sorteberg 2022
[56] Cappelen 2021a
[57] Cappelen 2020, 2021b

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according to a study of time series from West Greenland [58]. Improved models can account for much of the underestimation [59], but one should still be cautious when comparing fine-scale differences between two time periods.

3.1.2 Seasonal temperature and precipitation

There are significant seasonal differences in warming rates [60]. The cold seasons at high northern latitudes are warming more than summers. Winter (December-February) temperature at latitudes between 63° and 73° N had a warming trend from 1951 to 2021 between 2.5 and 2.7 °C (Figure 3.1), i.e., on average 0.52 °C per decade [61]. The trend for summer (June-August) for these latitudes and the same period was only 0.29 °C per decade (Figure 3.1). Spring (March-May) for these latitudes has warmed by 0.53 °C per decade, i.e., slightly more than winter, while autumn (September-November) has become 0.45 °C warmer per decade (graphics not shown for spring and autumn). Autumn (September-November) differs from the other three seasons by having a very strong latitudinal gradient in warming, with 73 °N warming 1.5 times faster than 63 °N. This is mostly due to steep gradients at longitudes east and west of the ArcticHubs study region, which is caused by slower development of sea ice in autumn [62]. The seasonal warming trends of the ArcticHubs study region largely follow the trends of high northern latitudes elsewhere (Figure 3.1). These warming trends have also been documented in a series of national and regional reports since the 1990s.

The high-latitude warming has led to longer thermal growing seasons; a trend analysis covering the period from 1950 to 2019 shows that the length of the thermal growing season of northern parts of Finland, Norway and Sweden with up to 3.5 days per decade, but that there is large heterogeneity over short distances [63].

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[58] Mernild et al. 2015
[59] Vejen et al. 2021
[60] Overland et al. 2017
[61] NASA 2022. Note: Linear trends 1951-2021
[62] Meier et al. 2021
[63] Aalto et al. 2022

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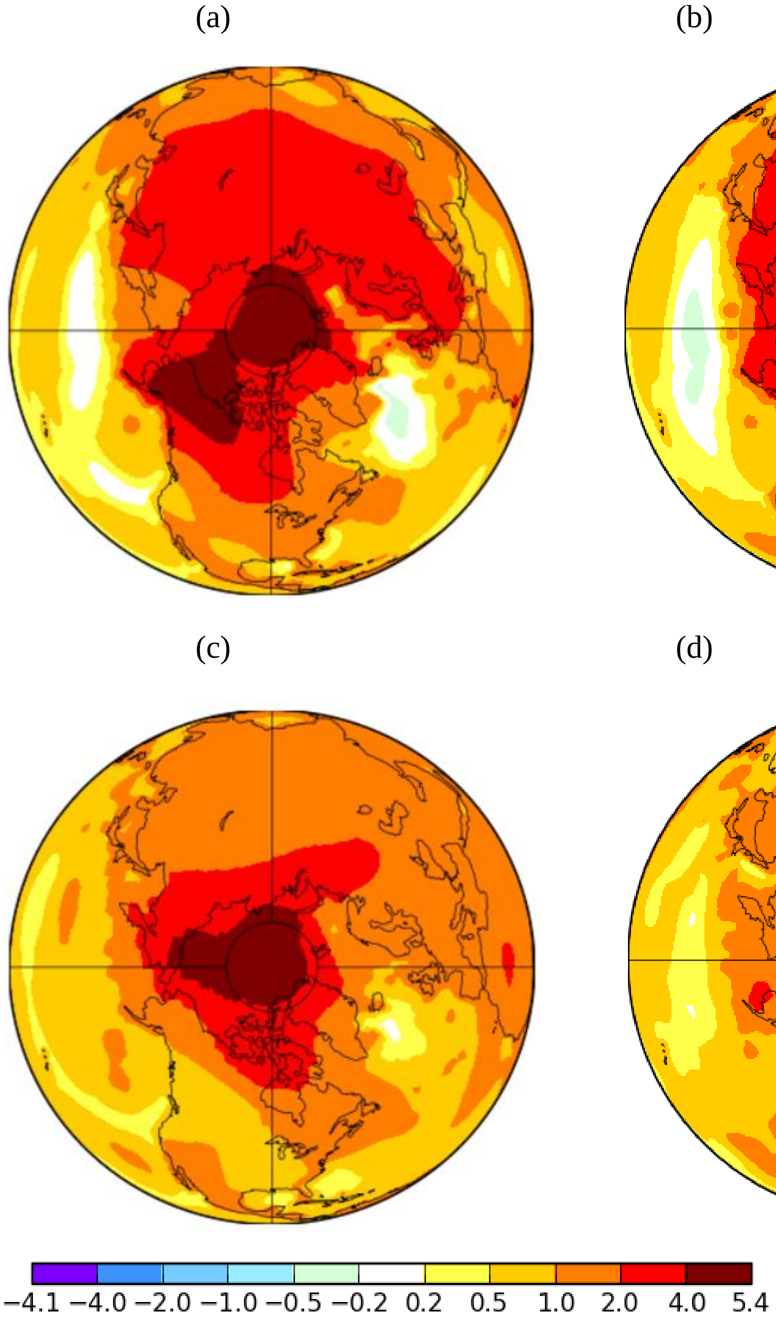

Figure 3.1. Temperature trends in the northern hemisphere for the period 1951-2022. (a) winter (Dec-Feb), (b) spring (Mar-May), (c) summer (Jun-Aug), (d) autumn (Sep-Oct). Retrieved from NASA GISTEMP [64].

The strongest growing season increase of ca. 5 days per decade has taken place in coastal parts of northern Norway, which includes the coastal sections of the hub Kvalsund-Kautokeino. The

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[64] NASA 2022. Note: Linear trends 1951-2022 for winter and spring and linear trends 1951-2021 for summer and autumn.

more continental parts of this hub have had an increase of ca. 3-4 days per decade, while the lowlands of Swedish and Finnish hubs have had a modest increase of 2-3 days per decade. Uplands of the same hubs have had an increase of less than 1.5 days per decade. These trends in growing season length are strongly correlated to changes in growing season degree days sum, which for the Norwegian, Finnish, and Swedish hubs vary between 0 and 40 degree-days per decade. Note that the thermal growing season is defined as the period of suitable conditions for plant growth, and is, hence, not equivalent to the biological growing season, which is the actual period of plant growth; see section 4.1.1 for trends in vegetation productivity. An important factor for discrepancies between the thermal and the biological growing season is the plants' hibernating state, which is not switched off easily by warmer temperatures. The earlier in the year with temperature conditions suitable for growth, the deeper is the hibernation (frost hardening) and hence, the more unlikely it is that plants will start any physiological activity; but see section 4.2 on impacts of premature dehardening in plants.

Seasonal trends for precipitation largely follow the whole-year trends, meaning that all seasons have become wetter in recent decades, however with some discrepancies from this general trend, as is shown in the next paragraphs.

Circumpolar high-latitude (poleward of 60 °N) total annual precipitation, i.e., both rainfall and snow, increased by 9 % from 1971 to 2019, driven by a 25 % increase in rainfall, with no overall snowfall trend [65]. Box et al. conclude that the largest precipitation increase north of 65 °N has taken place during the freeze-up season from October through May – when temperature increases are the greatest – especially along the south-eastern coasts of Greenland and Iceland, across the northern North Atlantic and the Barents Sea and in the vicinity of Svalbard.

For the ArcticHubs' land areas poleward of 60 °N, there is considerable variation in total annual precipitation. Annual precipitation at the northernmost parts of the Svalbard hub has increased substantially; there is large variation over short distances, thus the increase spans between 40 and 100 mm, and the majority of this is due to increasing snowfall rates. The trend metric in mm is described as a "linear regression temporal slope multiplied by the timespan in years".

Areas close to the Egersund hub (Egersund at 58° N, treatment covers areas northwards of 60° N), has even higher precipitation increases, exclusively caused by increases in rainfall. Westfjords on Iceland has had a minor total increase in precipitation, but with a strong local gradient: annual rainfall at the north-western side of the hub has increased by 60-80 mm, while

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[65] Box et al. 2022

rainfall on the south-eastern side has barely increased (0-20 mm). Snowfall in Westfjords has declined with 20-40 mm.

Most land areas in hubs of northern Finland, Norway and Sweden have all become wetter from 1971 to 2019, with increases between 0 and 60 mm during this period [66]. The interior Swedish-Finnish border area has the strongest trend, while coastal sections of the hubs Varangerfjorden and Kautokeino-Kvalsund, have, according to this model, no net change or may have become slightly drier. However, when it comes to rainfall only, all hubs in northern Finland, Norway and Sweden have received more, while snowfall shows opposite trends. The exception is the above-mentioned Finnish-Swedish border area that has a weakly increasing snowfall trend (0-20 mm). The Nuuk hub in western Greenland show negligible annual trends, but substantially increasing rainfall and decreasing snowfall trends, according to the ERA5 dataset.

In the next paragraphs, we dive deeper into precipitation trends relevant for the project’s industries, relying on other sources than ERA5, focussing primarily on seasonal trends.

For northern Norway, the five-year running mean shows that nearly the entire period since 1990 has been wetter than the normal for 1961-1990 [67]. The most recent 5-y period is 35 % wetter than 1961-1990 and 50 % wetter than 1915-1925. Spring (March-May) is similarly wet (140 % of 1961-1990 normal), while summer (June-August) precipitation has undergone minor change, being ca. 8 % wetter than the 1961-1990 normal. There has been major year-to-year fluctuation in summer rain since the 1950s, while the period from 1902 to 1950 was generally much drier. Autumn, on the contrary, is in a declining trend. The current situation (2011-2020) is a 10 % reduction in autumn precipitation compared to the 1961-1990 normal. Still, autumn precipitation is currently slightly higher than the 1900-1950 average. Autumn weather in the Kola Peninsula has also become slightly drier, at least in a dataset ending in 2015 [68]. Autumn is also the season in northern Sweden that differ slightly in trend from the other seasons. While the other three seasons have become significantly wetter, autumn shows an increasing trend, but this trend is only near-significant, i.e., P-value is between 0.05 and 0.10 [69].

Relative autumn precipitation values (% of 1991-2020 average [70]) from 1961 to 2021 from nine meteorological stations in northern Finland do not show any significant linear temporal changes (P-values for each station between 0.13 and 0.67). Five-year running means suggest no

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[66] Box et al. 2022, based on ERA5 data.
[67] Meteorological Institute of Norway 2021
[68] Marshall et al. 2016
[69] Chen et al. 2020
[70] Finnish Meteorological Institute 2022

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significant precipitation change for northern Finland as a whole (average of all nine stations: *r* = 0.213, *P* = 0.112). However, four of the nine stations do show significant increasing trends. These stations are Tornio (*r* = 0.289, *P* = 0.029), Kittilä (*r* = 0.293, *P* = 0.027), Inari (*r* = 0.373, *P* = 0.004), and Enontekiö (*r* = 0.426, *P* < 0.001). Particularly, it is a wet period from 2007 to 2016 that causes these significant trends (Figure 3.2). For these stations, this period was ca. 15 % wetter than the preceding 42-year period (1965-2006). The autumns of 1989 and 1990 were exceptionally dry. The northern Finnish meteorological stations show a relatively uniform trend for the other three seasons, i.e., winter, spring, and summer, for the 1961-2021 period. Trends are strongest for winter, where most stations show below-average values until the mid-1990s, thereafter primarily above-average values.

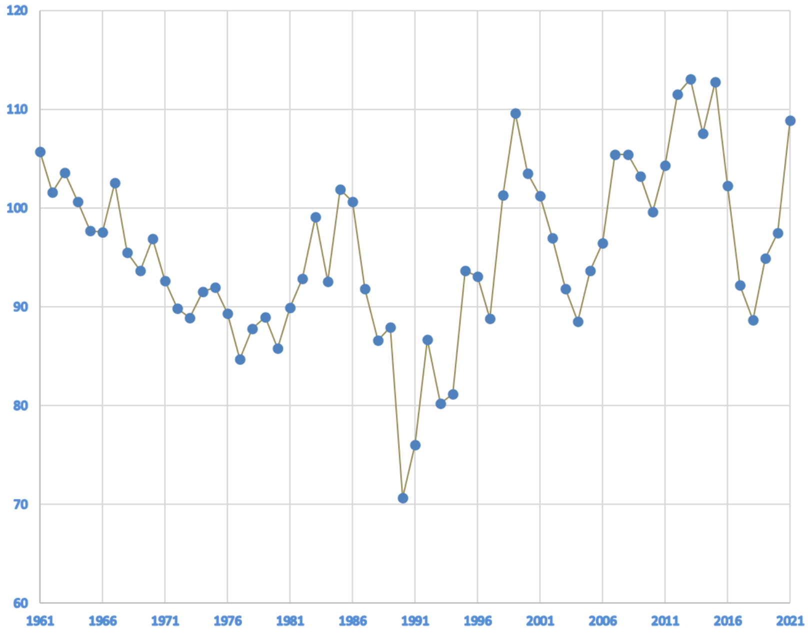

Figure 3.2. Five-year running mean of autumn precipitation in northern Finland covering four of the Finnish hubs (average of four meteorological stations; see text for details). Note: “2021” is the average of 2017-2021. Data retrieved from the Finnish Meteorological Institute.

3.1.3 Growing season dynamics using satellite data analysis based on GIMMS data

Our own analyses (Table 3.1) based on GIMMS satellite imagery (1982-2020) from the Nordic countries, the Kola Peninsula and adjacent Russian border regions south of Kola (Figure 3.3) confirm a clear significant trend towards an earlier onset of the growing season for the whole area (9.4 days earlier; *p* < 0.01; Table 1, second column). This is in fact a somewhat later onset as compared to the trend for the period 1982-2011 [71]. However, trends are highly contrasting between regions within this study area. The growing season of the northern oceanic region, including the coastal sections of the hub Kvalsund-Kautokeino, is delayed by 3.3 days over the 1982-2020 period ($p < 0.05$). The northern intermediate region (including Gran, Jokkmokk, Varangerfjord, Kovdor and Khibiny) shows the strongest delay in onset of growing season with 5.2 days ($p < 0.01$), while the onset of the growing season in the northern continental region (Kautokeino, Kittilä, Gällivare, Gran, Kemijärvi, Kemi, Malå and Inari) is delayed by 4.1 days ($p < 0.01$). The reason for these delays is most likely related to increasing snow depths in parts of the Nordic Arctic region and Kola; see treatment in section 3.1.4.

The southern intermediate region, which includes Kemi, contrasts strongly to the abovementioned regions. The onset of the growing season advanced by 16.7 days ($p < 0.01$) from 1982 to 2020. The southern oceanic region, which includes the hub Egersund, has an advance of 18.8 days ($p < 0.01$).

Vegetation greenness peaked progressively later for all northern regions during the period from 1982 to 2020. The delay was strongest in the northern continental region, where peak time has shifted with almost a week (Table 1, third column). The end of the growing season (= start of autumn), tend to occur later for all regions, but was only significant for the southern regions (Table 1). For the whole study area, the end of growing season was delayed by 10.4 days ($p < 0.01$), contributing to an increased length of the growing season of 19.7 days ($p < 0.01$).

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[71] Høgda et al. 2013. Note: 1982-2011 trend: 11.8 days for Fennoscandia and 19.3 days for the southern oceanic region

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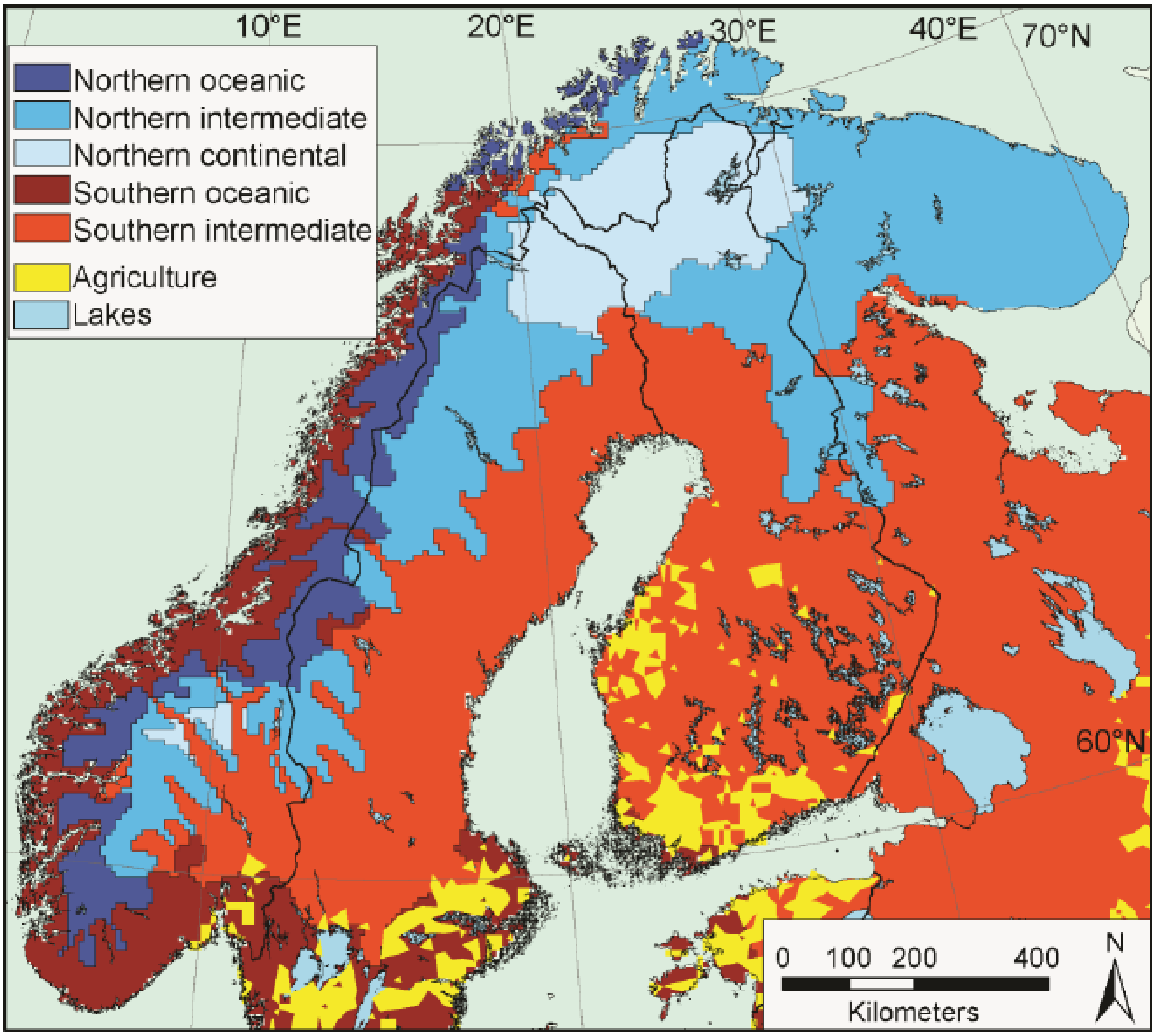

Figure 3.3. Map of regions described in section 3.1.3. Map reproduced from Høgda et al. [72].

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[72] Høgda et al. 2013.

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Table 3.1. Trends for different parameters extracted from the GIMMS-data based on NOAA-AVHRR data for the climatic regions of Fennoscandia, including parts of Russia (see map, Figure 3.3).

GIMMS data	**Trend Onset Spring**	**Trend peak time**	**Trend Autumn**	**Trend length**	**Trend Peak/Maximum**	**Trend Integrated NDVI**
Region	**1982-2020**	**1982-2020**	**1982-2020**	**1982-2020**	**Peak/Max** **1982-2020**	**1982-2020**
North-Oceanic	3.29*	1.71	2.40	-0.89	0.01	0.02
North-Intermediate	5.20**	1.41	1.30	-3.89	0.03**	0.25**
North-Continental	4.07*	6.79	2.59	-1.48	0.031*	0.20*
South-Oceanic	-18.83**	-1.55	15.12**	33.96**	0.10	0.19**
South-Intermediate	-16.72**	-1.45	15.13**	31.85**	0.035**	0.42**
All regions	-9.36**	-0.07	10.35**	9.71**	0.03**	0.32**

* = $p < 0.05$, ** = $p < 0.01$

3.1.4 Terrestrial snow season

The steadily increasing winter warming has had strong impacts on the snow season in the ArcticHubs study region, affecting both the duration of the snow season and the properties of the snow cover (thickness, hardness, wetness, etc.) [73]. A satellite-based analysis of land areas north of 60 °N, excluding Greenland, covering the period 1972-2014, showed a reduction in snow cover duration corresponding to 3.8 days per decade [74]. Snow cover extent (SCE) in Eurasia was anomalously large in 2016, while the last year on record, 2021, had the 5th lowest SCE in a dataset starting in 1967 [75]. Since 2006, Eurasian June SCE has been below the long-term average for all but one year. The trend on the North American continent is nearly identical.

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[73] Bokhorst et al. 2016, Vikhamar-Schuler et al. 2016, Brown et al. 2017, Rixen et al. 2022
[74] Estilow et al. 2015
[75] Mudryk et al. 2021

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Long-term trends for total Arctic SCE, are −3.8 ± 1.9 % per decade, and −15.5 ± 5.8 % per decade for May and June, respectively (1981-2021).

Eurasian snow cover trends are generally not representative for snow cover trends within the north-western European study regions of ArcticHubs. Snow seasons in the northern parts of the Nordic Region show high interannual variability, partly caused by variation in cyclone activity, which affect predominating patterns of wind, weather, and energy balance, including albedo [76]. Moreover, even if the Nordic Arctic Region (i.e., Norway, Sweden and Finland north of ca. 65° N) are becoming warmer also in winter, mean temperature in winter is still well below freezing. This, combined with a generally wetter atmosphere [77], can result in major snowfalls events. As an example, the meteorological station in Kautokeino, Finnmark, northern Norway, had a snow depth of 64 cm on 5 January 2022. In a 68-y long snow observation dataset, this day of year had never previously had such deep snowpack [78]. The general pattern, both in long-term records and the most recent 20-year period, is that snow seasons are highly variable; a 25-year dataset (1990-2014) from a coastal site in Troms, northern Norway, showed a 9-fold year-on-year variation in cumulative snow depth with a similarly extreme variation in cumulative soil frost [79]. Long-term snow observations from two sites in northern Norway, one continental and one coastal, are shown in Figure 3.5 [80]. The upper panel is a composite of two stations in Kautokeino/Guovdageaidnu, while the lower panel is from Tromsø.

This 52-y long dataset from Kautokeino manifests an increasing trend in maximum snow depth (based on our own calculations; $r = 0.333$, $P = 0.016$), but not in cumulative snow depth (i.e., sum of daily snow depth measurements; $r = 0.198$, $P = 0.160$). This increasing trend in maximum snow depth was also confirmed gridded observation-based data modelling covering the years from 1958 to 2017 for Troms; the interior parts of Troms, including areas close to Kautokeino, show increasing trends of up to 60 % in the parameter “winter maximum snow water equivalent” [81].

The last day of snow in spring in Kautokeino tends to come earlier ($r = -0.332$, $P = 0.018$). However, this does not affect the length of the snow season, which shows no significant temporal trends ($r = -0.181$, $P = 0.210$) over this 52-y period. A study from Finnish Lapland covering winters until 2014, also documents increasing snow depths [82]. A study from

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[76] Vikhamar-Schuler et al. 2016, Brown et al. 2017
[77] Marshall et al. 2020
[78] Meteorological Institute of Norway 2022
[79] Bjerke et al. 2015
[80] Norwegian Climate Service Centre 2022 (Observations and weather statistics)
[81] Dyrrdal et al. 2020
[82] Luomaranta et al. 2019

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Kobberfjord near Nuuk hub at western Greenland found that snowmelt timing is crucial in defining the beginning of the growing season and the growing season length [83].

Figure 3.4. Snow-draped birch trees after a blizzard. Photo: Jarle W. Bjerke ©

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[83] López-Blanco et al. 2017

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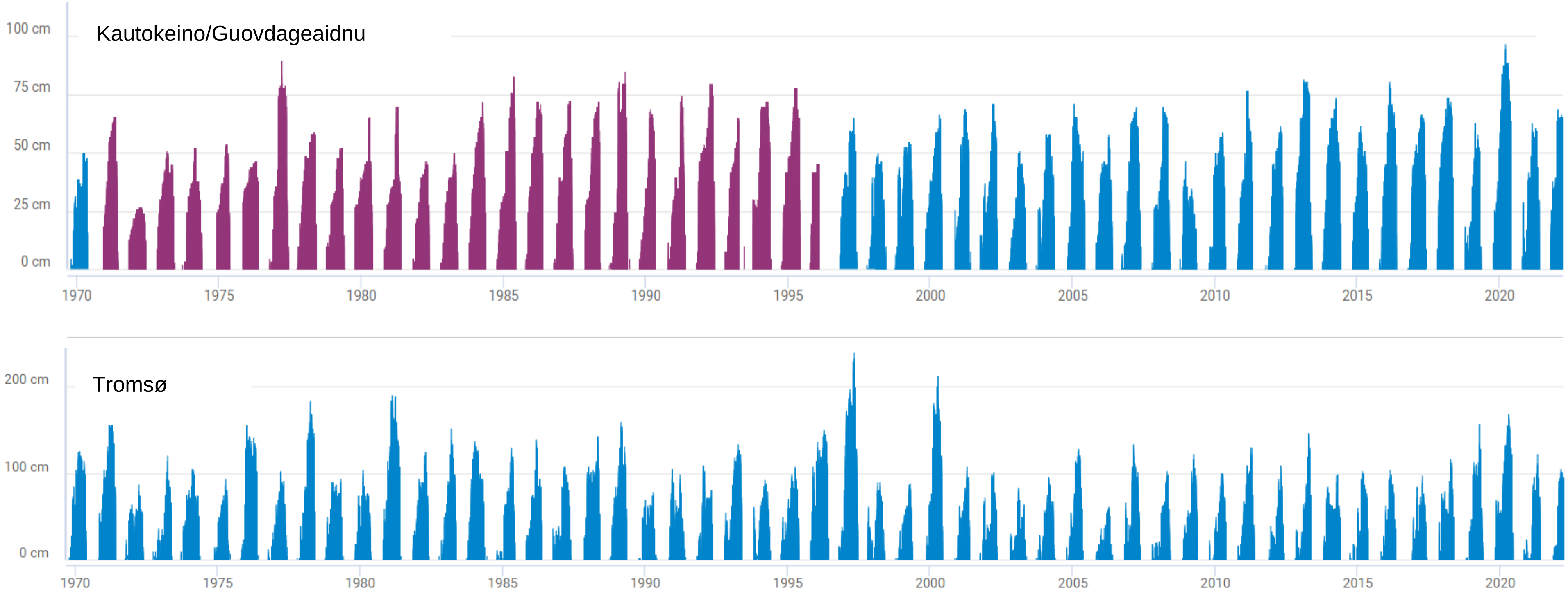

Figure 3.5. Snow depth observations from two weather stations in northern Norway from the winter 1969/70 to 2021/22 (last winter not complete at the time of production) to show how variable snow seasons can be in terms of maximum and cumulative snow depths.

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A general feature for the Arctic is that the onset of the growing season largely defines the end of the growing season, because once plant growth is initiated after the snowmelt in northern ecosystems, it continues only for a fixed number of days until the occurrence of senescence [84].

The long-term snow depth measurements from the northernmost part of Sweden (Norra Norrland, i.e., Lappland, Norrbotten and Västerbotten), covering the winters from 1949/50 to 2021/22, show large interannual variation in number of days with snow cover and no significant temporal trends [85]. While the period 1949/50 to 1966/67 mostly had winters with lower-than-average snow cover duration, the period from 1967/68 to 1998/99 had longer-than-average snow cover duration (reference period 1961-1990). Except for two winters, all winters from 1999/2000 to 2020/21 had lower-than-average snow cover duration. This latter period, however, does not differ from the first period (1949/50-1966/67) of this time series.

In the Swedish mountain region, the snow depth measurements undertaken since 1913 in Abisko provide strong indications of increasing long-term trends in snow depth. Maximum snow depth was considerably thicker in the period 1956-2004 than in the period 1913-1955 [86]. Average maximum snow depth for the 1913-2004 dataset was 51.5 cm. Snow depth data from the winter seasons 2004/05 to 2021/22, retrieved from the Swedish Meteorological and Hydrological Institute [87], show that the average maximum snow depth in this latter 17-y period was 77.5 cm, i.e., a 50.3 % increase compared to the 1913-2004 average. Also, within this 18-y period, there is an increasing trend of maximum snow depth (Figure 3.6). This is a clear indication that upland regions of northern Sweden follow the same increasing snow trend as adjacent regions in Norway and Finland; see treatment above.

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[84] Zona et al. 2022
[85] Swedish Meteorological and Hydrological Institute 2022
[86] Kohler et al. 2006
[87] Swedish Meteorological and Hydrological Institute 2022c

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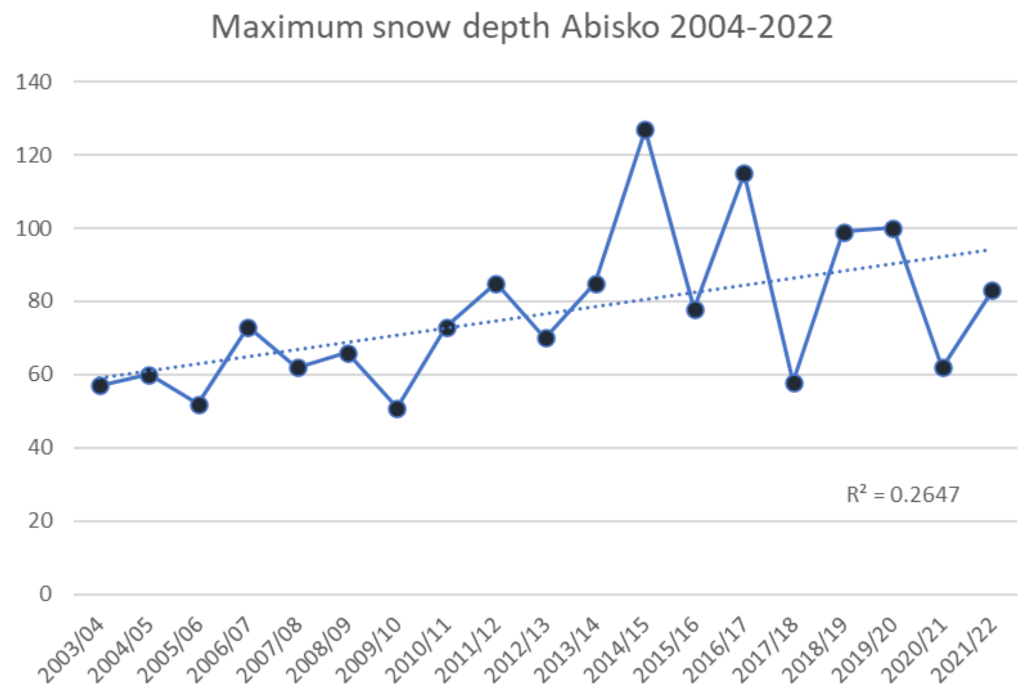

Figure 3.6. Maximum snow cover in Abisko, northern Sweden, winters 2003/04-2021/22, covering the period not included in Kohler et al. [88]. Snow depth in cm. $r = 0.515$, $P = 0.022$.

In contrast, the long-term snow depth data from Nuuk in West Greenland (1958-1981) had a 4.5% higher maximum snow depth (to 95 cm; SD = 57 cm) compared to a recent time series (2008-2018: to 91 cm; SD = 36 cm) from a neighbouring site located 16 km away from the Nuuk time series that stopped in 1981 [89]. According to these observations, not only maximum snow depth is slowly declining, but also its interannual variability.

The uplands in the Finnish-Norwegian-Swedish border region treated above are within a small area of Scandinavia that has experienced increasing snow cover fractions (SCF) after the turn of the millennium (2001-2016), according to a pan-arctic study relying on MODIS satellite imagery data [90]; see Figure 3.7. This area with increasing SCF partly covers the hubs Gällivare, Kittilä and Kautokeino-Kvalsund, whereas other minor areas with increasing trends (minute blue dots in Figure 3.7) possibly cover parts of the hubs Inari and Varangerfjord.

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[88] Kohler et al. 2006
[89] Cappelen 2020, López-Blanco et al. 2020
[90] Eythorsson et al. 2019

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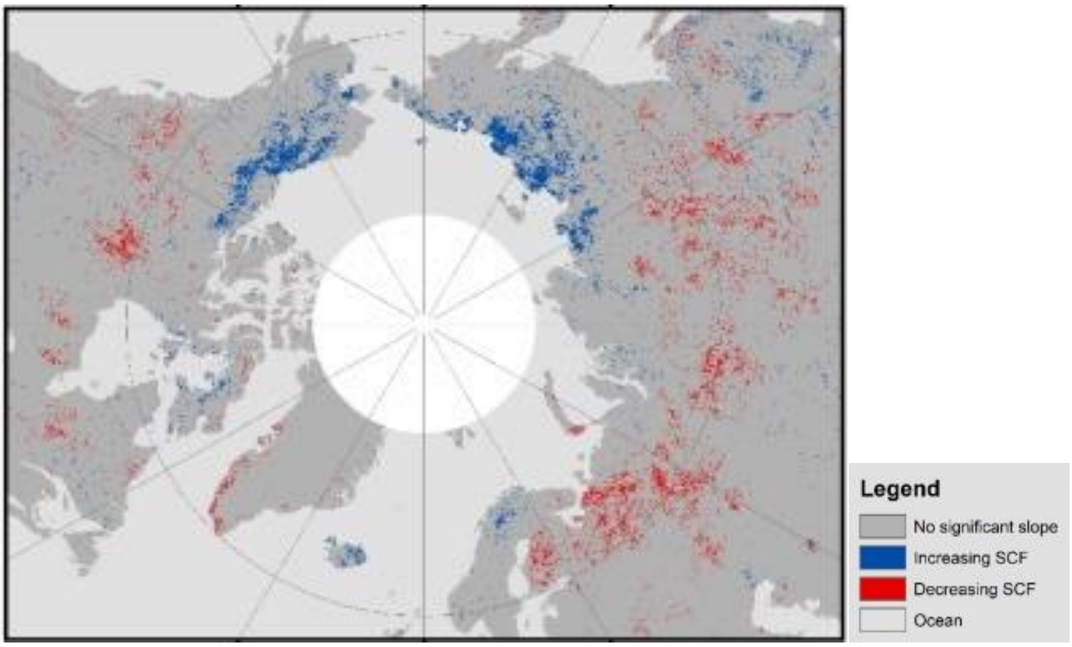

Figure 3.7. Areas of significant slope in snow cover fraction (SCF), at significance level $\alpha = 0.05$ using the Sen's slope estimator for the period 2001-2016. Blue: increasing SCF, red: decreasing SCF. Reproduced from Eythorsson et al. (2019). Disclaimer: Before this figure is reproduced in any public report, permission must be applied.

This figure thus largely shows the same trends as those of the recent AMAP report [91] treated in the first part of this chapter. However, while the AMAP report includes years until 2019, and in such context provides more updated information, the study by Eythorsson et al. [92] includes significance analyses to evaluate whether any trends are significant or not. This figure also shows that snow cover in most of the ArcticHubs study region was stable from 2001 to 2016 (grey areas). Notable exceptions are declining trends along the western coast of Greenland, including the hub Nuup Kangerlua (see also treatment above), declining trends in parts of Finland, immediately south of, or partly covering, the hubs Kemi and Kemijärvi, and increasing trends in large parts of Iceland, including the hub Westfjords in the north-westernmost part of Iceland. A study specifically focussing on Iceland confirms increasing snow trends for all months except October and November [93]. The increasing snow cover trends in Iceland are mostly restricted to upland areas and are associated with post-millennial significant positive

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[91] Box et al. 2022
[92] Eythorsson et al. 2019
[93] Gunnarsson et al. 2019

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trends of winter mass balance of Icelandic glaciers. In contrast, the longer trend from 1951 to 2019 in fact suggest declining snowfall trends for Iceland [94].

In ArcticHubs' northernmost hub, Svalbard, the snow season in spring is becoming shorter with ca. 2.8 days per decade, according to a time study of satellite imagery from 1982 to 2015 from Nordenskiöld Land, i.e., the area surrounding Longyearbyen [95].

Even more important than changes in the abovementioned snow depth and snow cover metrics for vegetation, wildlife and society are changes in snowpack properties. The steadily milder atmosphere during winter increases the frequency of rain falling on snow, which results in hard, icy layers on top of, and within, the snowpack during freeze-thaw cycles [96]. This topic is covered in further detail in Chapter 3.2, while predictions for snow until Year 2100 are covered in Chapter 4.1.

3.1.5 Soil and permafrost

In sections 3.1.1 to 3.1.3 we described air and surface conditions. Climate change in soil largely follow the aboveground trends, meaning that soil temperature increases when air temperature increases. There is large spatiotemporal heterogeneity in the global offset between soil and air temperature, often in the order of several degrees annually and up to more than 20 °C during winter months at high latitudes [97]. Such large offset is found in the most continental areas at high northern latitudes where an insulating snowpack causes the large difference between ambient and soil thermal conditions. While temperature differences between soil and air of the ArcticHubs regions are generally much lower, snowpack indeed has a strong insulating impact also here; see sections 3.1.3 and 3.2.2 for biological impacts to snowpack disturbance.

Long time series on soil temperature are less frequent than standard air temperature time series. Thus, there are comparatively few reports on soil temperature trends, especially from the ArcticHubs study region. Petersen [98] summarizes recent studies from around the World, and most studies show a warming trend. However, none of the studies cited by Petersen are from the ArcticHubs region. Petersen analysed a soil dataset from Hveravellir, a weather station in the Icelandic highlands, ca. 150 km SW of the hub Westfjords. During a 42- year period, from

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[94] Box et al. 2022
[95] Vickers et al. 2021
[96] Bjerke et al. 2014, 2015, 2017, Hansen et al. 2014, Turunen et al. 2016, Vikhamar-Schuler et al. 2016, Serreze et al. 2021, Rasmus et al. 2021
[97] Lembrechts et al. 2019, 2022
[98] Petersen 2021

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1977 to 2019, soil warming was significant in all months except May and June. This coincides with the snowmelt period, which varies much in duration between years. The warming trends at this site were largest in autumn and winter, showing a delay of 2-3 weeks in autumn cooling. The annual trend at 50 cm depth was 0.22 °C per decade.

An extensive Russian soil temperature dataset includes locations in the Kola Peninsula adjacent to the Russian hubs of ArcticHubs (Figure 1.1). These monitoring sites are close to Finland and Norway. The time series for these Kola sites, covering the period from 1975 to 2016, show a warming trend of 0.1 to 0.5 °C per decade in annual mean temperature at 80 and 160 cm depth [99].

A 25-year long time series of freezing soil measured by frost tubes (hence not monitoring exact temperature – only whether soil at depths down to 2 m is frozen or not) from a subarctic coastal grassland in northern Norway showed large interannual variation and no significant temporal trends [100]. The multi-model analysis of this time series showed that number of snow-free days with freezing temperatures was the primary regulator of duration and depth of freezing.

Earth materials (soils, sediments, bedrock) that hold year-round freezing temperature are termed permafrost. Temperature in permafrost is increasing both in Eurasia and North America [101]. The Nordic and Greenlandic monitoring sites follow this pan-Arctic trend. For example, at the monitoring site at Tarfala at 1 550 m.a.s.l. located ca. 120 km north-west of the centre of Gällivare (see Figure 1.1), permafrost temperature has increased by ca. 0.80 °C since 2000. The Svalbard station at Kapp Linné has had an increase of 1.50 °C since 2000, while the site Janssonhaugen – also on Svalbard – has had an increase of ca. 1.45 °C since 2000.

3.1.6 Coastal environment

Primarily because of melting glaciers, sea level is rising [102]. Another factor causing sea level rise is the expansion of seawater as it warms. Since 1900, global sea level has risen with ca. 205 mm, half of which has taken place since 1993 [103]. The most recent update shows that the increase since 1993 is 101.2 mm, viz. an average annual increase of ca. 3.5 mm.

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[99] Chen et al. 2021
[100] Bjerke et al. 2015
[101] Wolken et al. 2021, Box et al. 2022
[102] The IMBIE Team 2020
[103] Shaftel 2022

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Sea level rise is affecting coastal parts of the hubs, but impacts will be more severe during the next decades. Finnmark (including the hubs Kvalsund-Kautokeino and Varangerfjorden) and south-western Norway (including the hub Egersund) are among the areas of Norway that will be experiencing the most rapid sea level rise at national level [104]. The recent sea level rise in Norway has, however, been much lower than the global average, partly due to land uplift, but sea level varies much between the various parts of the country. Stations near Egersund have had a recent (1991-2020) increase of ca. 3.3 mm per year, while stations near Kvalsund-Kautokeino have had an increase of ca. 3.6 mm per year, and annual rates are accelerating [105]. Recent sea level change in Iceland is estimated to be 0.9-1.6 mm per year [106].

Sea level rise is a concern in coastal areas, due to the risk of sea water damage. The combination of storm surge and sea level rise is already causing severe damage to infrastructure, but also to coastal ecosystems [107].

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[104] Simpson et al. 2015
[105] Breili 2022
[106] Jóhannsdóttir 2020
[107] Brisson et al. 2015, Aarrestad et al. 2015, Simpson et al. 2015, Jóhannsdóttir 2020, Zinke 2022

3.2 Changing frequency of extreme weather (ca. 1981-2021)

Nature and nature-based industries are vulnerable to any seasonal deviations from long-term averages in temperature, precipitation, snow cover and other vital elements of climate. While minor deviations from long-term averages can be stimulatory, larger deviations are mostly negative. A typical example of a stimulatory minor departure is a growing season that is slightly warmer (1-2 °C) than the long-term average, leading to higher-than-normal primary production. However, if it gets too warm, drought conditions may take effect resulting in lower-than-normal primary production.

Large, short-term deviations from seasonal normals are termed “pulse weather”. The most deviating types of pulse weather are generally considered as being “extreme”. The Intergovernmental Panel on Climate Change (IPCC), the European Environment Agency (EEA) and other organizations early distinguished between the impacts of gradual change in essential climate variables and the impacts of changes in the magnitude or frequency of extreme weather [108]. Extreme weather and its equivalent term “extreme climate event” refer to a weather or climate event that is rare at a particular place (and, sometimes, time of year) including, for example, heat waves, cold waves, heavy rains, periods of drought and flooding, and severe storms [109]. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than a particular percentile (e.g., 1st, 5th, 10th, 90th, 95th, 99th) of a probability density function estimated from observations expressed as departures from daily or monthly means.

Extreme climate events have substantial negative impacts on human society and natural ecosystems. In this section 3.2, we summarize the current state-of-the-art for extreme weather that occur in the ArcticHubs study region and discuss these weather types in light of climate change.

3.2.1 Storminess, extreme precipitation, and inland floods

Precipitation and wind in northern Europe depend crucially on horizontal advection of moisture from remote regions [110]. European windstorms are intense and related to travelling cyclones associated with larger areas of low atmospheric pressure, and they occur most frequently during winter, although there are certain occurrences in all seasons [111]. Cyclone activity in the North

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[108] Intergovernmental Panel on Climate Change 2001, European Environment Agency 2004, Jentsch et al. 2007
[109] National Academies of Sciences, Engineering, and Medicine 2016
[110] Trenberth 1999, 2011; Hov et al. 2013
[111] European Academies Science Advisory Council 2013, Walsh et al. 2020, 2022

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Atlantic has increased at a rate of six events per decade [112], and this trend is largely due to increase in November and December, consistent with a diminished sea-ice cover [113]. Mesoscale low-pressure systems, commonly known as 'polar lows', are some of the most intense Arctic cyclones. Historically, such cyclones have led to loss of numerous boats and lives at open sea and along the coasts of the North Atlantic [114]. Polar lows develop rapidly when cold air flows over open water and are most common in the high latitudes of the North Atlantic, but there are no indications of any trends, partly because of little available information on historical frequencies of such mesoscale cyclones [115]. Polar lows often hit land and are associated with heavy snowfall, avalanche risk, and dangerous driving conditions.

The lack of evidence on cyclone activity trends results in limited knowledge on trends in high-wind events at high northern latitudes [116]. However, increasing trends in maximum snow depth in certain uplands of the Nordic Arctic region (see section 3.1.3) may be considered an indication of increasing impacts from polar lows, and hence also increasing frequency of windstorms.

The northernmost hub, Svalbard, is warming rapidly, and especially so in winter. Winter weather on Svalbard is characterized by cold, stable high pressure interrupted by warmer, wetter low-pressure systems traveling northwards along the North Atlantic storm track [117]. Atmospheric circulation conducive to elevated precipitation, wind speeds, and air temperatures near Svalbard are associated with increased avalanche activity in Nordenskiöld Land, i.e., the areas surrounding Longyearbyen [118], which has led to a recent increase in avalanche-induced loss of human lives [119].

As shown in section 3.1.1 there are increasing trends in annual and seasonal precipitation, and the relative change in extreme precipitation is expected to increase faster than the mean [120]. Walsh et al. [121] discussed the challenges of assessing historical trends in extremes of precipitation in the Arctic. A sparse network of gauges and a severe gauge undercatch in windy places are some of the reasons why such assessments are challenging. Still, valuable trend data

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[112] Rinke et al. 2017, Walsh et al. 2020, 2022
[113] Moore 2016, Walsh et al. 2020, 2022
[114] Syse 1979, Amdahl 2022
[115] Walsh et al. 2020, 2022
[116] Walsh et al. 2020, 2022
[117] Hanssen-Bauer et al. 1990, Rogers et al. 2005, Hancock et al. 2021
[118] Hancock et al. 2021
[119] Hovelsrud et al. 2020
[120] Sillmann et al. 2013; Myhre et al. 2019
[121] Walsh et al. 2020, 2022

exist; northern Europe is one of the few regions globally where there is high confidence that human influence has contributed to increasing frequency of extreme precipitation [122].

A large database of daily rainfall events from 281 sparsely distributed weather stations in Finland provide further support to the northern European trend. Using data from 1961 to 2016, this Finnish dataset identified statistically significant increases in extreme precipitation in some parts of the country including Lapland, and particularly during summer and fall seasons [123].

The case of flooding events at high northern latitudes was recently treated extensively by Walsh et al. [124]. They showed that, while temperature and sea ice rank at the high end of the spectra of evidence for change and confidence in future change, flooding rank at the lower end of the spectra. Here, we provide a brief overview of flooding events, focussing on the ArcticHubs study region.

River floods on inland plains are generally more persistent than river floods in steep valley terrains, but shorter-lasting floods in steep valleys can also have large impacts on floodplain ecosystems and human infrastructure. Hydropower dams have been constructed on several of the large rivers in the Nordic Arctic region. While such dams have major environmental impacts above and below the area of construction, the dams may help in alleviating flooding impacts by reducing water height during flood situations [125]. For example, in the Kemijoki river, which is the second largest river basin in Finland, the most severe floods took place more than 100 years ago. They had severe impacts on the entire city of Rovaniemi, which is surrounded by river channels. During the two recent major spring flooding events, in 1993 and 2020, i.e. occurring after completion of several dam projects and local flood prevention infrastructure development, only a few buildings and roads suffered from damage [126].

A time study of Norwegian catchments, covering the years from 1962 to 2012, identified decreasing flood frequencies in northern Norway because of decreasing trends in the frequency of snowmelt-dominated floods [127]. The study also shows that the timing of snowmelt-dominated floods has shifted and is occurring earlier. A 40-year long time series from a Svalbard glacial catchment revealed that a 2-week earlier onset of snowmelt-driven floods, large increases in autumn flows, prolongation of the hydrologically active season (starts earlier and lasts longer), and a decrease in flows in the latter half of June and the early part of August. This resulted in a

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[122] Seneviratne et al. 2021
[123] Pedretti & Irannezhad 2019
[124] Walsh et al. 2020, 2022
[125] Räsänen et al. 2020, Goytia 2021
[126] Räsänen 2021
[127] Vormoor et al. 2016

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change from snowmelt-dominated to a bimodal flooding regime with peaks in both summer and autumn [128].

Iceland has two other types of floods, namely glacier outburst floods and volcanically triggered floods [129]. Warming-induced glacier outburst floods also occur on Greenland and Svalbard, and to a lesser extent from glaciers in Sweden and Norway [130]. In Greenland, ice-dam failure causes frequent flooding. With the proximity of the Greenland glacier lakes to the coast this means that most proglacial channels in Greenland are flood-hardened and most landscape impact is likely to be offshore in estuaries and fjords. Smaller ice-dam events drain only a small fraction of the lake volume, are more frequent than large events, and have much less environmental impact. It is expected that glacier outburst floods will increase in frequency due to more extreme rainfall events and increasing velocity on ice melt.

Flash floods often occur in the warm season caused by extreme rainfall events. Flash floods can cause great geomorphological changes and have fatal consequences for ecosystems, humans, livestock, and infrastructure [131], also within the Nordic Arctic region [132].The combination of increasing frequency of extreme rainfalls and increasing number of river channelization structures will likely lead to increasing number of flash flood events with severe socio-economic costs, also within the ArcticHubs study region [133].

3.2.2 Winter warming events

As shown in Section 3.1, the snow season is changing more than the warm season at high northern latitudes. The temperature threshold at 0 °C for when water will be in liquid or solid state is a strong regulator of all life at high northern latitudes. Thus, temperature trends affecting the predominance of freezing vs. thaw weather have major implications for human life, ecosystems, and nature-based industries. In northern coastal regions where open sea water modulates temperature, mean winter temperature is rather close to the freezing temperature threshold [134]. However, this changes over short distances inland. Continental sections of the Nordic Arctic region, and similarly continental parts of Nuup Kangerlua in western Greenland,

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[128] Osuch et al. 2022
[129] Björnsson 2010, Carrivick & Tweed 2019
[130] Rachlewicz 2009, Carrivick & Tweed 2019
[131] Blöschl et al. 2020, Moraru et al. 2021, Kahle et al. 2022
[132] Bjerke et al. 2014, Lawrence 2016
[133] Lawrence 2016, Räsänen 2021
[134] Skagseth et al. 2008, Førland et al. 2009.

traditionally have a much drier and colder winter climate than nearby coastal sections, which means average winter temperature well below freezing.

Weather events that result in unseasonally warm winter temperature may or may not be considered extreme. This depends on how rare a particular event is in terms of deviation in temperature from the long-term average for that time of the year, the duration of the event, and how it affects society and nature. An event covering a large region may be considered extreme in some parts of the region but not extreme in other parts of the same region. For the ArcticHubs study region, the crossing of the 0 °C temperature threshold is an important aspect when evaluating whether a warming event is extreme or not. In coastal regions, where thaw periods and rainfall events occur nearly every year in the middle of winter, may not be considered extreme from a meteorological viewpoint.

For the Nordic Arctic region, such yearly events are traditionally restricted to the most oceanic regions of Nordland and Troms, including Lofoten, Vesterålen and the outer (westernmost) coastline of the islands of Senja, Kvaløya, Ringvassøya and neighbouring small islands [135]. Similar rainfall-dominated winter climate is prevalent in the lowlands of Iceland, including the hub Westfjords, while Faeroe Islands including the hub Suðuroy has an even warmer and more oceanic climate. Here, nearly all precipitation during winter falls as rain in the lowlands, while snow is, or at least has been, more common above 500 m above sea level [136]. Terrestrial ecosystems in these oceanic landscapes are much more tolerant to temperature fluctuations around the freezing point than more continental ecosystems.

Warm events during winter in the Nordic Arctic region are associated with cyclone activity i.e., westerlies bringing in warm and humid air from the sea [137]. Thus, warm events are associated with high precipitation rates, which for most of a cyclone's life falls as rain – at least along the coast and in the lowlands. Rainfall may result in complete snow thaw, destroying the subnivean environment that under normal winter conditions protects short vegetation and wildlife (e.g., rodents and invertebrates), against the harsh ambient winter environment [138]. Impacts on ecosystems are treated in more detail in Chapter 4.

After a winter warming event, temperature returns to freezing. Meltwater and remaining snow refreeze, and vegetation surfaces that experienced full snowmelt during the warming event are exposed to more severe freezing than experienced in the subnivean environment to which they

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[135] Moen 1999, Bakkestuen et al. 2008
[136] Hansen 1966, Einarsson 1984, Tukanen 1987, Ólafsson et al. 2007,
[137] Hanssen-Bauer et al. 2003, Akperov et al. 2018
[138] Bjerke et al. 2014, Williams et al. 2015, Bokhorst et al. 2015, 2016

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are adapted. Remaining snow is turned into a hard crust, which does not insulate as well as an airy snowpack not affected by thaw weather. Under such conditions, soil freezes deeper than normal and may result in delayed soil thaw. Deep soil frost can be persistent and have large negative consequences on infrastructure, agriculture, and ecosystems far into the growing season [139].

Several hubs have repeatedly been negatively affected by winter warming events since the turn of the millennium. These impacts are described in chapters 4 and 5.

3.2.3 Summer drought

A study covering mid to high latitudes found a sixfold increase in historical northern hemisphere concurrent large heatwaves during the snow-free season May-September [140]. The ArcticHubs study region includes a summer climate gradient from very wet to relatively dry areas, i.e., from highly oceanic (Faeroe Islands, Iceland) to continental (north-eastern Finland, Svalbard, parts of Greenland) climates [141]. Summer drought is a rare event in the more oceanic-influenced parts of the study region, but even there, drought occasionally occurs. For example, an atmospheric dipole blocking in July 2009 led to the driest month in Iceland in a 19-year study period, from 2001 to 2019 [142]. The drought of summer 2009 led to much lower-than-average vegetation greenness (NDVI), as measured by satellites, indicating drought-induced reduction in plant vitality. A very dry period in June 2019 also led to drought in Iceland replenishing rivers and having negative impact on the salmon fishing season with the fish unable to swim upstream to complete their breeding cycle [143]. The entire year of 2019 was in fact very dry in Iceland; western parts of the island received less than 60 % of normal precipitation, with a small area receiving less than 40 % [144]. In particular, the period from March to June was very dry. The month of June 2019, and the entire summer, was also very warm and dry in parts of Europe, in June with a centre in northern Poland and Germany, and with warmer-than-average temperatures northwards to the hubs in northern Sweden [145]. These heatwaves over Europe in summer 2019 contributed to the advection of anomalously warm air over

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[139] Kullman 1989, DeGaetano et al. 2001, Brown & DeGaetano 2011, Bjerke et al. 2015
[140] Rogers et al. 2022
[141] Tuhkanen 1984
[142] Olafsson & Rousta 2021
[143] Anonymous 2019
[144] Bissolli et al. 2020
[145] Bissolli et al. 2020, Sulikowska & Wypych 2020

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Iceland, and over Greenland, which led to several temperature records and extreme glacier melt events [146].

For more information on future drought frequency and drought-induced impacts, see sections 3.3 and 4.2.

3.3 Climate projections until 2100

Projections are unanimous: the world, including all its regions, will become warmer. Global surface air temperature will continue to increase until at least mid-century under all emissions scenarios considered, and global warming of 1.5 °C and 2 °C will be exceeded during the 21st century unless deep reductions in carbon dioxide (CO_2) and other greenhouse gas emissions occur in the coming decades [147]. High northern latitudes will be warming faster than the global average due to the 'Arctic amplification' phenomenon; the amplitude of Arctic mean warming will remain stable at roughly twice the global mean warming [148].

Waterbodies (oceans, lakes, rivers, glaciers, sea ice, permafrost) are also becoming warmer. Glaciers and sea ice are melting at an unprecedented rate. Arctic amplification is also taking place in oceans. The upper 2000 m of the Arctic Ocean warms at 2.3 times the global mean rate within this depth range averaged over the 21st century in the Coupled Model Intercomparison Project Phase 6 Shared Socioeconomic Pathway 5 (SSP5) scenario [149]. The SSP5 baseline corresponds to the previously used RCP8.5 scenario. By 2081-2100, the upper 700 m of oceans adjacent to all hubs will be 2.5 to 5.0 °C warmer than the 1981-2000 average. Svalbard, Varangerfjorden and the Finnish and Swedish hubs bordering the Bothnia Bay will experience the highest ocean warming, while the waters surrounding Faroe Islands will warm at a slower rate, being ca. 2.5 to 3.5 °C warmer in 2081-2100. This study shows that the Arctic Ocean warming will have an increasing rate, which can be attributed to the fact that the enhancement of ocean heat convergence into the Arctic Ocean will be greater than the increase of Arctic Ocean surface heat loss. Even the deep sea (below 900 m) will warm. The increasing ocean temperature will have consequences for planning of marine fish farming; see Chapter 5 for more information.

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[146] Hanna et al. 2021, Walsh et al. 2022
[147] Allan et al. 2021
[148] Wang M et al. 2022
[149] Shu et al. 2022

In the remaining part of this section, we look more closely into the climate projections for temperature, precipitation, and snow cover for the northern land areas poleward of 50° N (as shown in maps), focussing textually on the hubs and learning cases (Figures 3.8-3.11). The projections were extracted from the global climate model (GCM [150].) CMIP6 ECEarth3 products for the period 2015-2100 under the SSP585 scenario, which corresponds to the much-applied RCP8.5 scenario [151]. Note that all projections come with a degree of uncertainty. Generally, uncertainty increases with time range, meaning that there is larger uncertainty for 2081-2100 than for 2031-2050 [152]. In projections, uncertainty is often manifested as minor ups and downs over a longer time scale. Thus, the longer timer scale (for example from 2020 to 2100) can have a clear increasing or decreasing pattern, but at shorter time scales (for example 2030 to 2050), the same pattern may not be visible.

Figure 3.8 (a) shows the annual mean air temperature of land areas poleward of 50° N for the reference period 2015-20, while Figure 3.8 (b) shows the modelled annual mean air temperature of the same land areas for the period 2085-2100. The loss of area with mean annual temperature below 0 °C is particularly striking. For the years 2085-2100, only inland areas of Greenland, the high-Arctic islands of north-eastern Canada, interior upland areas in the Canadian-Alaskan border region, and highly continental upland areas of Siberia will still have an annual mean temperature below 0 °C.

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[150] From López-Blanco et al. 2022: *GCMs are dynamically self-consistent climate estimations and reconciled with atmospheric properties and physics, their variability is, as is generally the case for a freely running GCM, out of phase with the actual climate evolution as only the radiative forcing from greenhouse gases and other anthropogenic drivers are specified as boundary conditions. Natural modes of variability are as the models simulate them and hence not to be expected to be in phase with observed modes. A freely running climate model only takes information about the real-world time evolution of the climate through information on the overall external drivers (e.g., specified concentrations of greenhouse gases following a particular emission scenario) and therefore only represents the statistical properties of the weather (i.e., the climate) at any point in time, not the exact timing of the weather. This approach implies that naturally varying phenomena with an internal time scale from weeks to multiple years will not be in phase with that of the real-world climate system.*

[151] Lavoie et al. 2013, 2019, Coppola et al. 2021

[152] Collins et al. 2013

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Figure 3.8 (a)

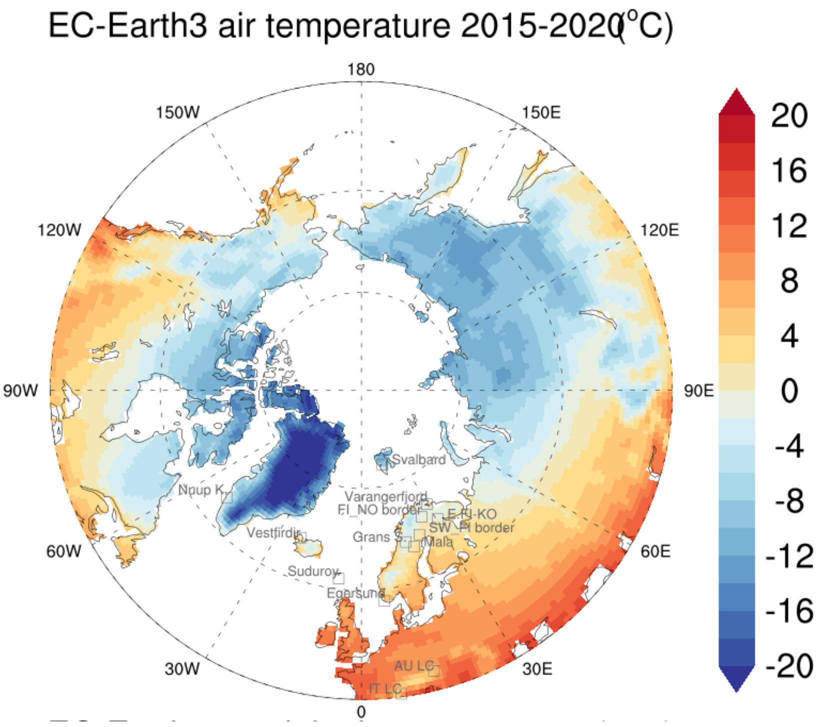
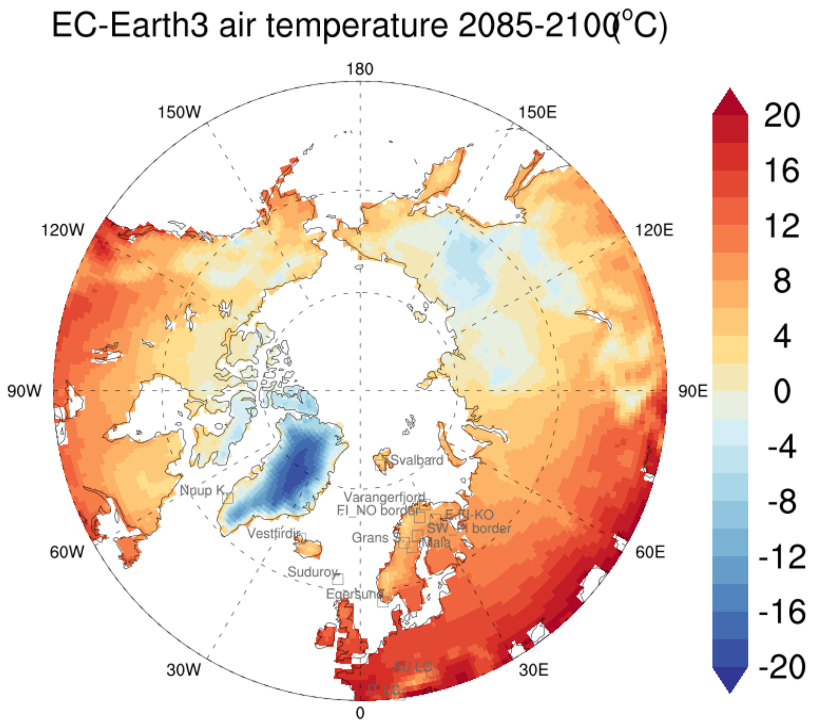


Figure 3.8 (b)



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(Figure 3.8 continued)

Figure 3.8 (c)

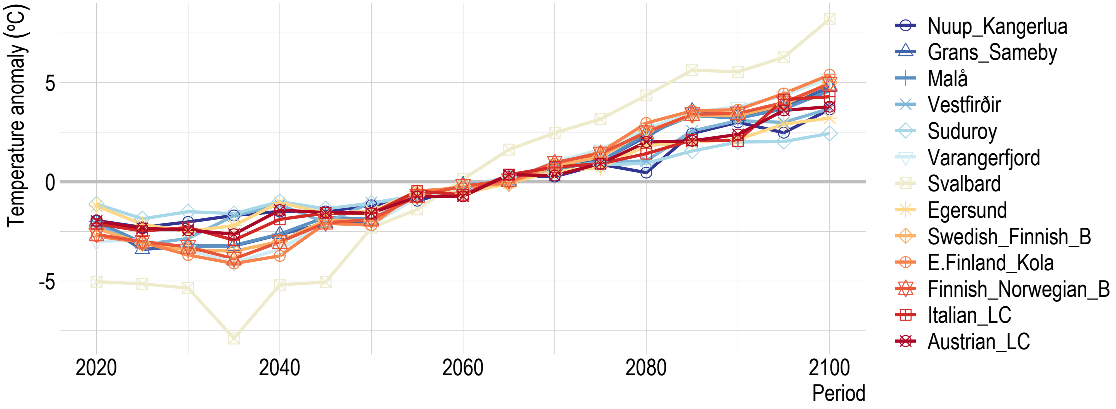

Figure 3.8. 21st century temperature projections for land areas poleward of 45° N. (a) Mean annual temperature for the reference period 2015-2020. Open squares with grey lines represent selected centre pixel for each hub (e.g., "Vestfirðir" = Westfjords), or group of hubs (e.g., "SW-Fi border") or learning cases (e.g., "AU_LC"). (b) Modelled mean annual temperature for the period 2085-2100 according to the CMIP6 EC-Earth3 model. (c) Time series extracts of 6-year anomalies (with respect to the 2015-2100 average) of recent and future air temperature in a selected centre pixel for each hub, or group of hubs or learning cases. Examples: "2020" = average of 2015-2020; "2040" = average of 2035-2040. Place name specifications: Vestfirðir = Westfjords. "Swedish_Finnish-B" = Swedish-Finnish border area, i.e., centre point representing hubs no. 1 (Kemi), 5 (Jokkmokk), and 8 (Gällivare); "E.Finland_Kola" = Eastern Finland and Kola Peninsula, i.e., centre point representing the hubs no. 2 (Kemjärvi), 3 (Inari), 16 (Khibiny Mts.), and 17 (Kovdor); "Finnish_Norwegian_B" = Finnish-Norwegian border area, i.e., centre point representing the hubs no. 4 (Kittilä) and 9 (Kautokeino-Kvalsund); "Italian_LC" = Italian learning cases; "Austrian_LC" = Austrian learning cases.

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As expected, the hub-specific (including learning case sites) temperature projections confirm the general warming trends. At the same time, these downscaled projections are useful for assessing the warming rate variations between sites (Figure 3.8 (c)). The arctic amplification effect results in more intense warming at the northernmost hub, Svalbard. In recent decades, the archipelago has warmed at a rate of 0.7-0.9 °C per decade [153]. By the end of the century, Svalbard will be 5.0-8.0 °C warmer than the 2015-2100 average (Figure 3.8 (c)).

By the end of the century (2085-2100) most other hubs and learning case sites will be from 3.0 to 4.5 °C warmer than the 2015-2100 average (Figure 3.8 (c)). At the lower end of the scale are the two southernmost hubs Egersund and Suðuroy with a temperature anomaly in 2100 at 2.5-3.0 °C. Nuup Kangerlua is also at the lower range. Despite having an arctic climate, it is situated ca. 14 latitudinal degrees south of the high-Arctic hub Svalbard. The amplification at higher latitudes explains why Svalbard is projected to warm much faster than Nuup Kangerlua. Still, the air temperature of a marine stretch in the Labrador Sea-Davis Strait area – just west of Nuup Kangerlua – is one of the areas that warmed quickest during the 1975-2014 period with a trend of 0.7-0.9 °C per decade [154]. This is largely related to sea ice decline [155], and shows that warming rates can be very “high-Arctic-like” also at latitudes well south of the Arctic Circle.

Precipitation models for northern land areas project increasing precipitation for most areas poleward of 60° N [156]. There will also be a significant change in the partitioning of snow and rain, i.e., a transition from snow to rain with major implications for winter snowpack [157]. The precipitation projections retrieved from the CMIP6 ECEarth3 products for the period 2015-2100 confirm increasing annual precipitation trends (Figure 3.9 (a-b)). The most striking changes will take place in the more continental regions of Eurasia and North America. For the ArcticHubs study region, all hubs will become wetter (Figure 3.9 (c)). However, the projections for the Central European learning cases are less clear; see fluctuating trend lines for Italian and Austrian learning cases (dark blue lines). There is a tendency towards reduced precipitation rates in the learning cases. A recent modelling study on the impacts of future Atlantic Sea surface temperatures on winter precipitation in the European Alps forecasts increasing winter precipitation until ca. 2040, followed by decreasing trends until ca. 2070 and then another

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[153] Wang et al. 2022
[154] Wang et al. 2022
[155] Meier et al. 2021
[156] Wang et al. 2022
[157] Vikhamar-Schuler et al. 2016, Landrum & Holland 2020, Ford & Frauenfeld 2022, Ye et al. 2021, Wang et al. 2022

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period of increasing trend until 2100 [158]. The trend lines in Figure 3.9 (c) for the Austrian and Italian learning cases largely follow the same ups and downs.

While there is a general increasing precipitation trend for all hubs (Figure 3.9 (c)), there is less hub variation in precipitation trends than it is for temperature trends; see treatment of temperature above. A general feature of the hubs is a relatively modest increase in precipitation until ca. 2050. The model projects an acceleration in precipitation change from ca. 2060 for practically all hubs.

While precipitation will increase, there will be a massive decline in snowfall. Snow extent for October to December will decline with as much as 60 % by 2100 relative to the 1995-2014 mean, according to CMIP6 projections based on the SSP5-8.5 scenario [159]. This is the emission scenario being tracked most closely by present emissions [160]. Similar reduction is expected for the April-June period. This is graphically shown in our assembly of CMIP6 projections for snow accumulation (Figure 3.10). Virtually the entire pan-arctic area will experience declines in snow accumulation (Figure 3.10 (a-b)). Only a highly continental area in north-eastern Siberia, within the Republic of Sakha (Yakutia), is projected increasing snow accumulation.

All hubs and learning cases currently with snow accumulation will have strong declines in snow by 2100 (Figure 3.10 (c)). The model projects the largest declines for the hubs Svalbard and Gran Sameby. The latter hub is the southernmost of the Swedish hubs, and the point from where the model data is retrieved is situated in the forested lowlands of this long and narrow hub, which stretches from the alpine zone at the Norwegian-Swedish border to the Bothnian Bay.

Some hubs will have slightly increasing trends until 2035, according to the model. This includes the Swedish-Finnish border area, the Norwegian hub Varangerfjord, and the Icelandic hub Westfjords. From ca. 2050, snow accumulation will decline in all hubs and learning cases.

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[158] Formetta et al. 2021
[159] Mudryk et al. 2020
[160] Walsh 2021

Figure 3.9 (a)

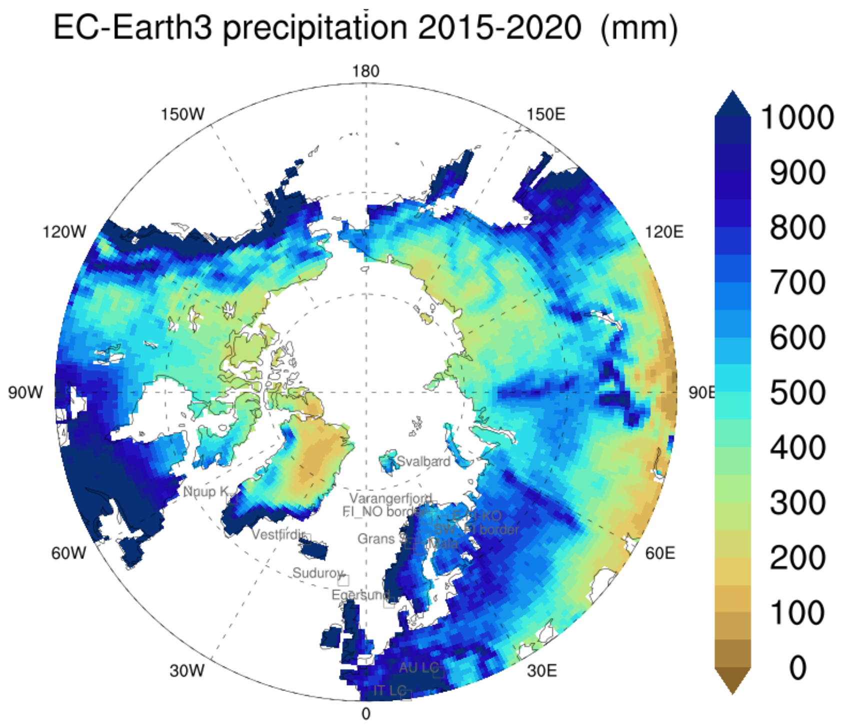
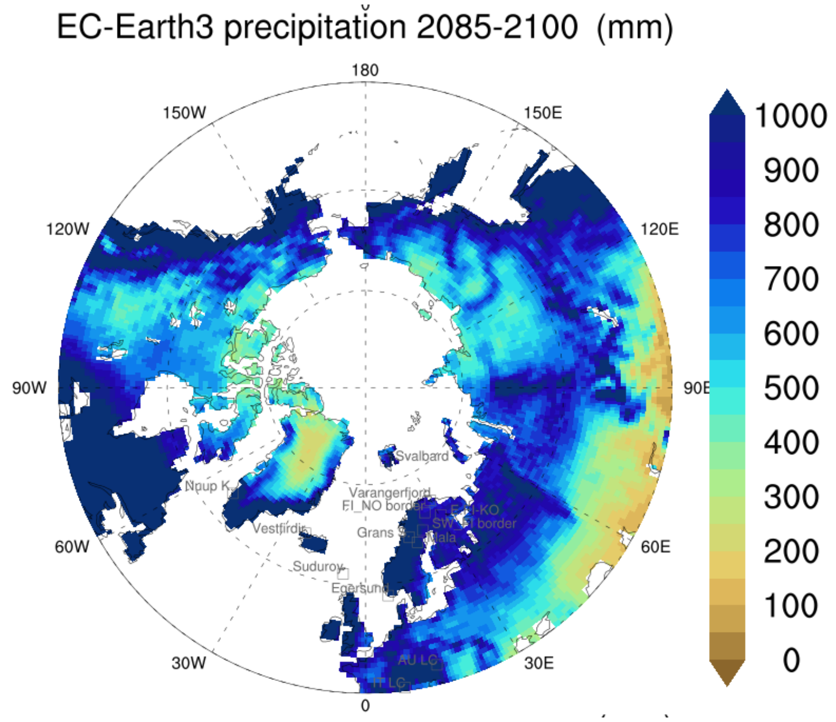


Figure 3.9 (b)



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(Figure 3.9 continued)

Figure 3.9 (c)

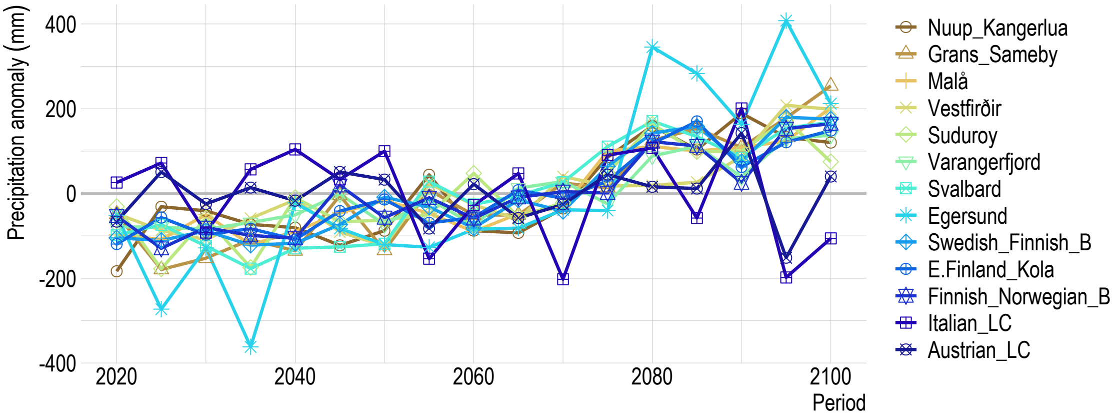

Figure 3.9. 21st century precipitation projections for land areas poleward of 45° N. (a) Mean annual precipitation rate for the reference period 2015-2020. (b) Modelled annual precipitation rate for the period 2085-2100 according to the CMIP6 EC-Earth3 model. (c) Time series extract of the 6-year anomaly (with respect the 2015-2100 average) of expected total precipitation in each pixel where there is a hub. See legend of Figure 7 for description of place names.

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Figure 3.10 (a)

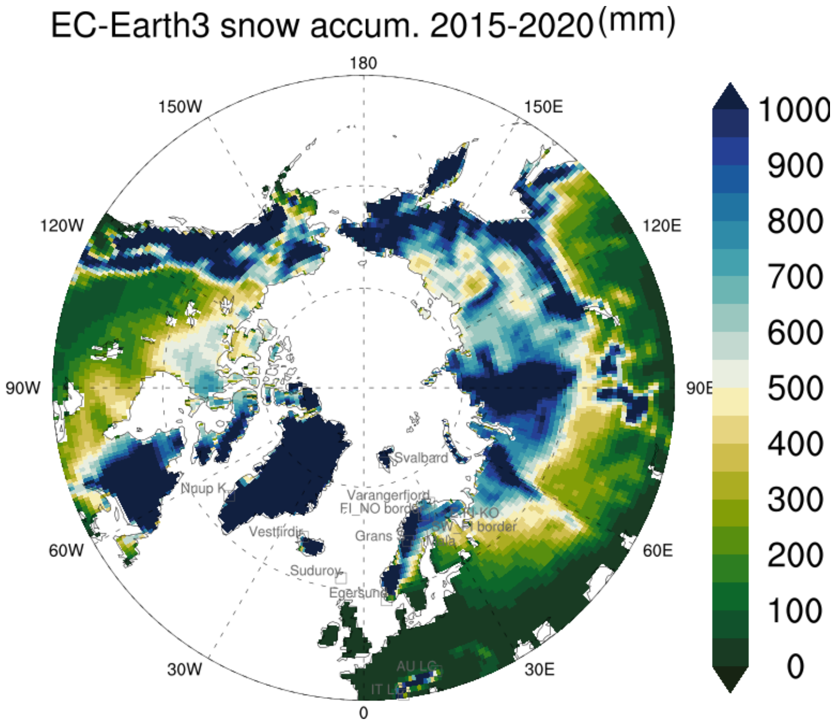
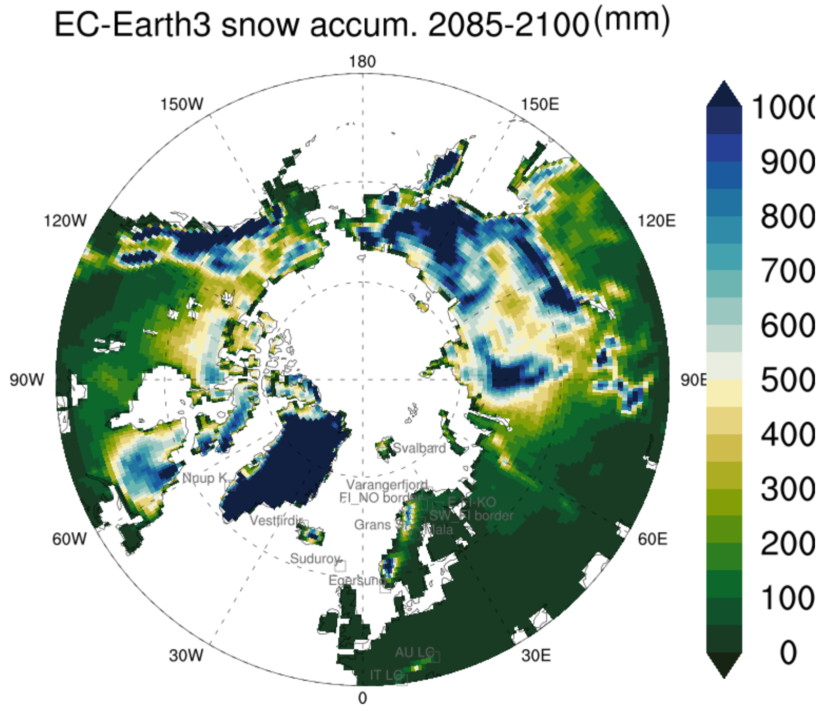


Figure 3.10 (b)



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(Figure 3.10 continued)

Figure 3.10 (c)

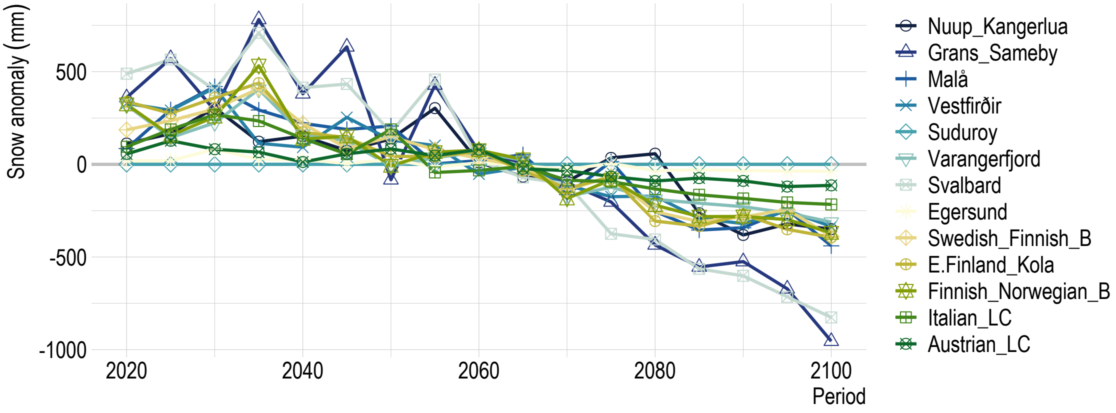

Figure 3.10. 21st century snow accumulation projections for land areas poleward of 45° N. (a) Mean annual snow accumulation for the reference period 2015-2020. (b) Modelled annual snow accumulation for the period 2085-2100 according to the CMIP6 EC-Earth3 model. Maps show the expected 6-year snow accumulation of land areas north of 45 °N between 2015-2020 and 2085-2100 according to CMIP6 EC-Earth3 model. (c) Time series extracts of 6-year anomalies (with respect to the 2015-2100 average) of recent and future snow accumulation in a selected centre pixel for each hub, or group of hubs or learning cases. See legend of Figure 3.8 for description of place names.

Finally, in Figure 3.11, seasonal plots of temperature, total (i.e., liquid and snow) precipitation, and snowfall are shown for each hub and learning cases (or groups of nearby hubs/learning cases), for the periods 2015-2020 and 2085-2100. The temperature graphs (top panel) show that monthly temperature of all hubs and learning cases will increase substantially from 2015-2020 to 2085-2100. The largest changes will take place at the northernmost hub, Svalbard, where July temperature is projected to be ca. 13 °C warmer than 2015-2020 and January temperature ca. 17 °C warmer.

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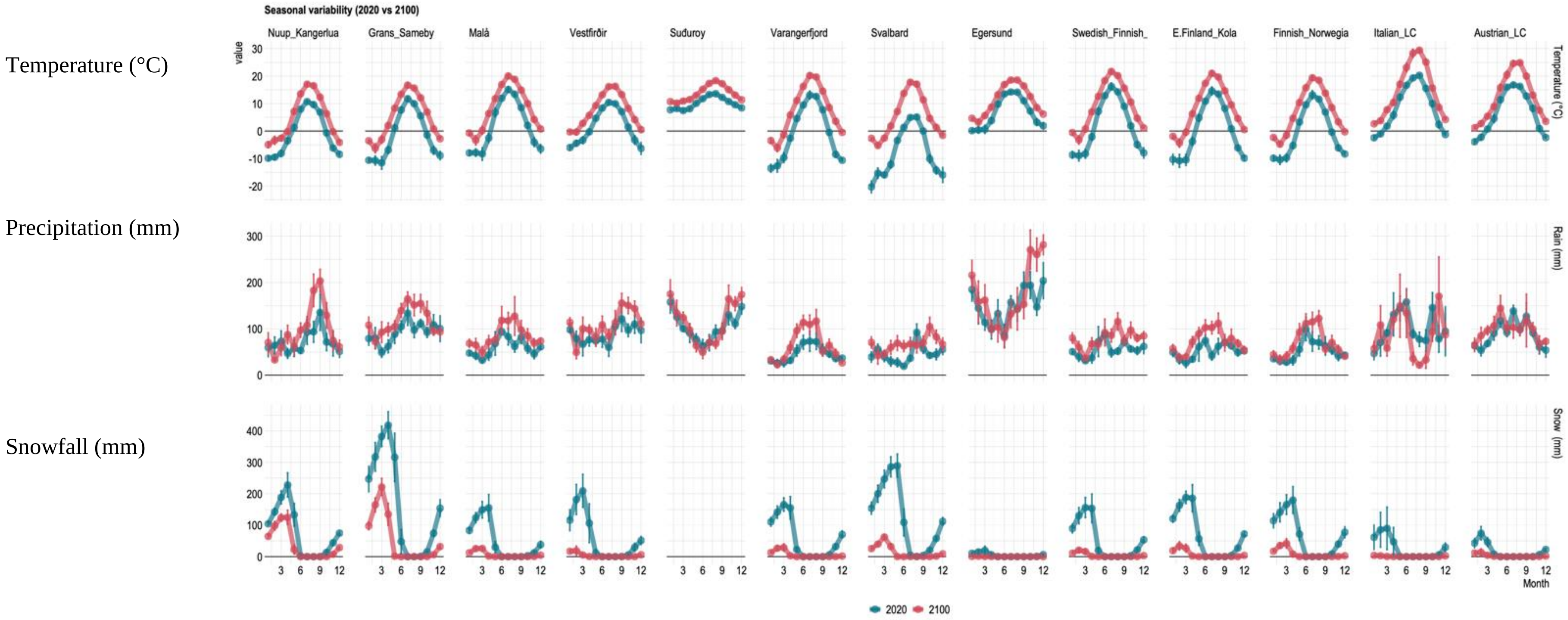

Figure 3.11. Seasonal variability (January to December) of air temperature, rain, and snow at each hub comparing the monthly 2015-2020 (turquoise) and 2085-2100 (red) averages according to CMIP6 EC-Earth3 model. See legend of Figure 3.8 for description of place names used.

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The high-altitude learning cases in Italy and Austria will also warm considerably, especially in summer (ca. 10 °C warmer than 2015-2020). The inland hubs of Finland, Norway and Sweden will warm considerably in wintertime; January will be 8-10 °C warmer in 2085-2100 than in 2015-2020. Mean temperature during the four coldest months (December-March) will be at or close to 0 °C.

Temperature in spring and autumn will also change considerably. For many hubs and learning cases spring will advance by at least a month, i.e., April monthly mean temperature in 2095-2100 will for most hubs be higher than May monthly mean temperature in 2015-2020. For example, in Gran Sameby, mean temperature during 2015-2020 crossed the 0 °C line in early April, while this crossing will take place in early-to-mid-March in 2085-2100. A similar delay in 0 °C crossing will take place in autumn for hubs currently with proper freezing winter climate.

Temperature change will be more modest at the very oceanic-influenced hub Suðuroy at the Faeroe Islands. The largest change will occur in August with a ca. 5-degree warming, while for most other months, temperature will increase by 2-3 °C.

Precipitation changes (Figure 3.11, middle panel) are generally more subtle than changes in temperature. There is also higher uncertainty related to precipitation changes (comparing length of error bars between precipitation and temperature panels). There is a trend towards the largest changes in precipitation in summer and/or autumn. This is the case for Nuup Kangerlua, Gran Sameby, Malå, Westfjords, Varangerfjord, and the inland hubs in northern Finland, Sweden, and Norway. For example, Nuup Kangerlua can expect an approximate 40 % increase in September precipitation rates, while there are no clear changes in precipitation rates for the period from November to March for this hub.

Snowfall (Figure 3.11, lower panel) and snow season duration will decline at all hubs and learning cases, except at Suðuroy, where all precipitation falls as rain even under the current climate. Snowfall in the most snow-rich month will only be a small fraction of current snowfall. For example, at the northern Finnish and Swedish hubs, snow accumulation will be ca. 20 % of current values. In the Finnish-Norwegian border area, for which the model states that April is currently the most snow-rich month, nearly all April 2085-2100 precipitation will fall as rain.

The same is the case for the most snow-rich month in Svalbard, May. In 2085-2100, all precipitation in May will fall as rain even at this high-Arctic site.

3.4 Changing frequency of extreme weather events 2022-2100

The current state of knowledge on projected changes of extremes in the Arctic was recently reviewed by The Arctic Monitoring and Assessment Programme [161]. The Intergovernmental Panel on Climate Change (IPCC) have also summarized projections on extremes for northern regions [162]. In this section 3.4 we summarize the current understanding of future impacts of extreme weather events, which rely on these sources, supplemented with results from primary research articles.

3.4.1 Cold seasons

Most regional climate models show an increase of cyclone frequency in winter (DJF) and a decrease in summer (JJA) to the end of the 21st century [163]. Within the ArcticHubs study region, increases in winter are projected to occur in the Barents Sea and north of Greenland, while decreases are projected in the Nordic seas, which is largely equivalent to the Greenland Sea, the Norwegian Sea, and the Iceland Sea. Reduced sea ice will enhance intensification of winter storms over the Arctic Ocean, by enhancing the surface turbulent heat fluxes and lessening static stability while also strengthening vertical shear of horizontal wind [164]. This means that future sea ice reductions (e.g., related to delayed autumn freeze-up) will likely enhance Arctic cyclone intensification in winter and spring and increase cyclone-associated precipitation.

The projected increase of annual mean precipitation at high northern latitudes will also result in increased frequency of extreme precipitation events [165]. As more of the precipitation in winter will fall as rain (see section 3.3), it is likely that there will be fewer snowstorms towards the end of the century in the entire ArcticHubs study region, even in the northernmost hubs such as Svalbard. Increased frequency of extreme rainstorms in winter will lead to increasing numbers of flash floods, more soil erosion and abrupt permafrost thaw where it is still present.

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[161] Walsh et al. 2020, 2022
[162] Collins et al. 2019, Hock et al. 2019, Meredith et al. 2019
[163] Akperov et al. 2019
[164] Crawford et al. 2022
[165] Walsh 2021, Walsh et al. 2020, 2022

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Snowstorm frequency will be declining, but will still occur, albeit at a lower frequency, and be restricted to the northernmost hubs, especially towards the end of the 21st century (Figure 3.10).

Rain-on-snow (ROS) events adversely affect humans, vegetation, hydrology, and wildlife, and further affect the local climate by altering snowmelt, runoff, and soil temperatures [166]. ROS events are projected to increase in frequency at continental high northern latitudes, such as the interior parts of Alaska, but will most likely decrease in more maritime-influenced areas [167]. Thus, winter rain will at a higher frequency fall on bare ground, and not on snow. Northern terrestrial ecosystems are adapted to the hibernating state provided by a permanent snow cover and frozen soils. Winter rain will thus affect ecosystems negatively in at least two ways: it will remove any remaining protective snow layer, and it will cause increased soil erosion.

Ecosystem-damaging winter warming events, which have increased in frequency over the past 50 years, are associated with fluctuations in temperature around 0 °C; see section 3.2. While freezing conditions are still prevalent at high northern latitudes, long and frequent periods of thaw weather with limited snow accumulation will become the norm for most northern regions during the 21st century; see Section 3.3. Thus, cold-tolerant ecosystems will have to quickly adapt (in ecological terms) to near-constant mild weather with sporadic freezing events. Even the most high-Arctic hub, Svalbard, will by 2071-2100 have an average midwinter (DJF) temperature close to 0 °C; recent (1971-2000) midwinter temperature on Svalbard Airport Longyearbyen is −13.9 °C, while median projected increase in midwinter temperature under an RCP8.5 scenario is 15.1 °C [168].

Thus, terminology will change from "winter warming events" to "winter freezing events" for most of the hubs and learning cases. "Winter freezing events" is a term already in use to describe damage in plants that grow in warm temperate and Mediterranean climates [169], and in cold-tolerant plants that are exposed to extreme freezing temperature regimes, often below −30 °C [170]. Long exposure to mild winter weather will reduce frost hardiness and/or disturb hibernation in plants, animals and soil microbiota. Thus, even short exposure to freezing weather in a thaw-dominated winter climate can have major damaging or even mortal effects. See section 4.3 for further information.

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[166] Bjerke et al. 2015, Cohen et al 2015, Walsh et al. 2020
[167] Bintanja & Andry 2017, Bieniek et al. 2018
[168] Hanssen-Bauer et al. 2019
[169] Hultine et al. 2018, Gonzalez Antivilo et al. 2020
[170] Beck et al. 2004, Man et al. 2021

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Sporadic episodes of atmospheric blocking may drive future winter climate changes in opposite directions than the overall trends. An example of such blocking occurred during the winter of 2012/13 resulting in a long period of easterlies and dry, cold weather in parts of Finland, Sweden, and Norway [171]. See next section (Growing season) on more information on atmospheric blocking and possible increase during the 21st century.

3.4.2 Growing season

For the summer seasons, the climate models simulate an increase of cyclone frequency over the Central Arctic and Greenland Sea and a decrease over the Norwegian and Kara Seas by the end of the 21st century [172]. It implies that the hub Westfjords on Iceland will be more affected by heavy winds and rainstorms in summer seasons during the 21st century, while hubs in Finland, Norway, Sweden, Kola and western Greenland will be less affected.

Still, all hubs will become wetter (see Section 3.3), and episodes of heavy rain are expected to increase because of a moister and warmer atmosphere, and such episodes will result in an increasing frequency of flash floods, surface water, rock avalanches, landslides, permafrost thaw, and soil erosion [173]. Increasing frequency of such events is already ongoing in several hubs, especially the northernmost hub, Svalbard, where flash floods, permafrost degradation, landslides and thermokarst development have increased in frequency.

While summer climate will become wetter, warming will induce increased evaporation. In addition, earlier snowmelt will result in lower water volumes in rivers during summer months. Overall, for the Finnish, Norwegian and Swedish hubs, this leads to increasing probability for summer drought and forest fire risk during the 21st century [174].

An uncertainty for future climate, and hence for distribution of precipitation, is the future frequency of atmospheric blocking events. Such blocks can remain in place for several days or even weeks and are the driver of several extreme climatic events, since affected areas have the same kind of weather for prolonged periods [175]; see descriptions of such blocking events in Sections 3.2.3 and 3.4.1. There is a clear increasing trend of northern hemisphere blocking occurrences since 1965 [176]. Europe is identified as a dominant region of blocking in most indices, due to the configuration of a strong, meridionally tilted storm track upstream of a large

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[171] Iden et al. 2012, Kristiansen et al. 2013, Bjerke et al. 2017a, Treharne et al. 2019

[172] Akperov et al. 2019

[173] European Academies Science Advisory Council 2013, Hanssen-Bauer et al. 2015, O'Gorman 2015, Kharin et al. 2018, Sorteberg et al. 2019, Dyrrdal & Førland 2019

[174] Hanssen-Bauer et al. 2015, Stensen et al. 2019, Chen et al. 2020, Eckdahl et al. 2022

[175] Woollings et al. 2018, Lupo 2020, Kautz et al. 2022

[176] Lupo 2020

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landmass, and blocking also occurs frequently over Greenland with strong downstream impacts on Europe associated with the negative phase of the North Atlantic Oscillation (NAO) [177]. Recent extreme droughts over eastern Europe and western Russia are driven by the occurrence of prolonged blocking episodes, as well as surface processes, and have become more common during the 21st century. Even to this day, weather and climate models tend to underestimate the duration and intensity of blocking [178], especially over Europe [179]. Thus, summer drought events and extreme rainfall may increase more than projected by large-scale climate models. For the ArcticHubs study region, it is not possible with the current knowledge to state with certainty which hubs will be affected the most by increasing atmospheric blocking events. A likely scenario is that there will be steadily wetter growing seasons interrupted by very dry growing seasons.

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[177] Davini et al. 2012, Kautz et al. 2022

[178] Woollings et al. 2018, Lupo 2020, Lupo et al. 2021

[179] Davini et al. 2021

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4 Ecosystem responses to climate change in the European Arctic

4.1 Ecosystem response to long-term gradual trends (1981-2021)

In this section, we review how recent climate change has affected ecosystems and wild species at various trophic levels and how other external factors potentially mask or override any impacts of climate change. This section 4.1 is not intended to describe trends for all species and ecosystems on land and in sea, but to present numerous representative examples from the deep sea to the highest peak to achieve a general overview of how gradual climate change has affected ecosystems during the last ca. 40 years. Red Lists for habitats and species from the various Nordic countries are valuable in this review. In addition, database searches for preparation of this section aimed to provide a balanced overview of various taxonomic and organismal groups – from unicellular algae via 30-tonne marine mammals to habitat types covering thousands of square kilometres within the ArcticHubs study region.

4.1.1 Long-term vegetation greenness trends

4.1.1.1 Review of published data

As documented in Chapter 3, the coldest hubs of the ArcticHubs study region have, on average, been warming more than the boreal (forested) regions of the study region. The most recently updated analysis on remotely sensed tundra greenness, published annually in the Arctic Report Card, shows a distinct increase in vegetation greenness of Arctic tundra since 1982 [180]. Increasing greenness means that there is an increasing amount of chlorophyll per measured surface area, i.e., increasing primary productivity. Trends from 1982 to 2021 are strongest over Canadian, Alaskan and East Siberian tundra, and this is closely linked to reduced sea ice and warmer growing seasons. Also, the hubs Nuup Kangerlua in Greenland, Westfjords on Iceland, Central Spitsbergen in Svalbard, and the coastal areas of Varanger in northernmost Norway show significant positive trends during this 40-year period. The higher-resolution MODIS dataset, starting in 2000, show more mixed signals. Westfjords, Svalbard and Varanger do indeed show positive trends from 2000 to 2021, while large ice-free regions of south-western

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[180] Frost et al. 2022: dataset from 1982 is the AVHRR GIMMS3g+; dataset from 2000 is the MODIS MCD43A4, version 6. Datasets include growing season of 2021.

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Greenland show negative trends, and this includes the western part of Nuup Kangerlua, while the hub's eastern parts closest to the continental ice sheet show positive trends. The declining greenness trends (negative trends are generally known as "browning") in the western parts of Nuup Kangerlua may be a result of increasing post-2000 trends in winter warming damage to evergreen shrubs [181].

The other hubs of ArcticHubs were not included in this analysis published in the Arctic Report Card, as they are not considered truly arctic from a bioclimatic viewpoint. The definition of arctic tundra follows the most recent framework of the Circumpolar Arctic Vegetation Classification (CAVM) [182]. Other sources must therefore be used to assess greenness trends in the hubs not treated by the Arctic Report Card. We have also done separate greenness trend analyses for the various hubs, focussing on a single central point within each hub. These trends are described below, but first, we summarize the most relevant published reports on NDVI trends.

For the non-tundra regions of ArcticHubs, there was a near-uniform trend of increasing vegetation greenness from 1982 to 2009 [183]. The trend was particularly strong in the conifer-dominated lowland regions of northern Sweden and northern Finland, i.e., the eastern parts of the Swedish hubs Malå, Gran and Jokkmokk, and the Finnish hub Kemi (see Figure 1.1 for hub locations). An updated map covering trends from 1982 to 2019 of the area poleward of ca. 55° N show highly mixed trends for the various hubs [184]. The Scandes mountain range including adjacent upland forests (covering western sections of most or all Swedish hubs), coastal sections of northern Norway including the Varangerfjorden hub, and south-eastern Iceland are areas with negative trends over this 38-year period. There are also smaller lowland areas in northern Sweden showing declining trends over this period. Both Westfjords and Svalbard show mixed signals, which means there are areas with declining trends adjacent to areas showing increasing trends. It is important to note that trends in this map are not tested for significance at pixel level. So, even if the trend for the whole area covered by this map is strongly positive and highly significant, trends for every individual pixel may not be. Year 2019 was quite abnormal in having the lowest mean NDVI for Eurasian and North American land surfaces since 2014. Frost et al. [185] suggested that low NDVI in 2019 was possibly due to lag effects arising from cold conditions a year earlier. A year later, in 2020, circumarctic NDVI

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[181] Weijers 2022
[182] Walker et al. 2018
[183] Buitenwerf et al. 2018, Chen et al. 2019, Piao et al. 2020
[184] Box et al. 2022
[185] Frost et al. 2020

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reached record-high levels, this time possibly due to lag effects arising from the warm conditions in 2019 [186]. Hence, while there is a highly significant 1982-2019 greening trend for the entire circumpolar area north of 55° N, pixel-level trends in the map should be treated with caution. Significance analyses at pixel-level (see Figure 3.7 for an example of pixel-level trends) combined with yearly updated maps, such as the maps included in the annual report "Arctic Report Card", would be valuable for interpreting trends for smaller areas within the larger boreal region north of 55° N.

The higher-resolution MODIS dataset starting in 2000 show mixed trends. For the period 2000-2018, there was indeed an overall greening of northern lands, i.e., land areas poleward of 60° N, but for the Nordic Arctic region the average increase per year was weaker than for the period 1982-2009. A rather large forest-dominated area in northern Sweden, protruding into northern Finland, shows declining greenness trends during this period [187]. Causes for this may be both climatic and non-climatic. Forest monitoring in northern Finland manifests that the growth rate of the dominant trees Scots pine (*Pinus sylvestris*) and birch (*Betula pubescens*) declined from 2000 to 2018 [188]. Suggested primary agents for this decline are snow and wind break, browsing ungulates, nutrient anomaly, and fungal diseases. Agents of less importance include frost damage, scleroderris canker (= *Brunchorstia* disease, which is a fungal infection of coniferous trees), soil wetness, among others. At national level, snow is by far the most important agent for damage to standing forest trees in Finland. This Finnish study did not consider the impacts of forestry practices.

Large boreal areas of northern Sweden (from ca. 64° to ca. 69° N) show declining remotely sensed greenness trends (i.e., browning) after 2000, see the MODIS vegetation greenness trends maps by Chen et al. and Piao et al. [189]. Increasing vegetation greenness at high northern latitudes, including the Nordic countries, is attributed predominantly to climate change [190]. However, there is, to our knowledge, no previous attempts of interpreting the declining remotely sensed vegetation greenness in Sweden and Finland that was reported by Chen et al. and Piao et al. [191]. We have not found evidence of any weather events or climatic trends that could have caused this decline.

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[186] Frost et al. 2021

[187] Buitenwerf et al. 2018, Chen et al. 2019, Piao et al. 2020

[188] Korhonen et al. 2021

[189] Chen et al. 2019, Piao et al. 2020

[190] Zhu et al. 2016, Piao et al. 2020

[191] Chen et al. 2019, Piao et al. 2020

On the Swedish side, there has been intensive clearfelling forestry since the middle of the twentieth century [192]. Due to a long history and extensive impact of industrial forest management, only a small fraction of intact boreal landscapes remains, according to some studies [193]. Clearfelling, i.e., industrial clear-cut forestry, is a factor to consider when trying to explain the abovementioned Swedish browning. The pattern of intensive clearfelling is also evident in Finland [194]. A large body of literature on Swedish forestry practices have been published recently. Here, we provide a brief summary, with the obvious risk of missing out relevant sources. We focus on some of the recent studies that have received most interest within the scientific community and in the general public. A pan-European study from 2020 by Ceccherini et al. [195] indicated high Swedish timber harvest volumes with large geographical extent. Several groups of scientists, including Wernick et al. and Palahí et al. [196] pointed out potential errors in the estimates in the 2020 study by Ceccherini et al. In their rebuttal, Ceccherini et al. [197] provided an amended analysis based on the points raised by Wernick et al. and Palahí et al., and these amended maps confirmed the original analysis demonstrating an increased harvest rate in clear-cuts in Sweden and Finland during recent years, but at lower levels than presented in the original analysis. Breidenbach et al. [198] argued that advancements in satellite-based mapping led to erroneous conclusions in the original study by Ceccherini et al. [199]. A later study from a separate research group (Zhou et al. [200]) applied a combination of methods to assess recent changes and trends in land cover, forest harvest areas, and soil erosion in the Nordic countries. They found a 4 % decrease in forested areas in Sweden from 1992 to 2018. Their spatial maps, showing transitions of forests to non-forest, largely overlap with the area showing declining vegetation greenness. Overall, for forest trends, they concluded that forest areas increased in Denmark, Finland, Norway at a similar rate, while forests in Sweden decreased steadily over the period covered (i.e., 1992-2018).

The topic of forestry intensity is beyond the core scope of this report. Therefore, the topic is here only treated briefly as a possible explanation for the abovementioned declining greenness trends detected by Chen et al. and Piao et al. [201] for parts of northern Sweden and northern

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[192] Mikusiński et al. 2021, Röstlund 2022
[193] Mikusiński et al. 2021, Svensson et al. 2019, 2020, 2022
[194] Mason et al. 2021
[195] Ceccherini et al. 2020
[196] Wernick et al. 2021, Palahí et al. 2021
[197] Ceccherini et al. 2021
[198] Breidenbach et al. 2022
[199] Ceccherini et al. 2020
[200] Zhou et al. 2021
[201] Chen et al. 2019, Piao et al. 2020

Finland. Overall, we may at least conclude that there is no evidence of any climatic factors causing the observed declines in vegetation greenness in this area.

4.1.1.2 GIMMS and MODIS data analyses for the hubs in the Nordic countries

Our own analyses for this report of GIMMS satellite imagery from the Nordic countries and Kola Peninsula confirm a positive trend in NDVI for the period 1982-2020, indicating an increase in biomass. GIMMS Maximum NDVI (Max-NDVI) increased by 0.030 ($p < 0.01$) from 1982 to 2020. This index includes data for the peak greenness around high summer for every single data point. On the other hand, the Time-Integrated NDVI (TI-NDVI) is an average of NDVI measurements from June, July, and August. TI-NDVI increased by 0.316 ($p < 0.01$) from 1982 to 2020. Thus, these two variants of remotely sensed vegetation greenness show nearly the same overall greening trend.

The northern continental region of the study area showed significant increases in both Max-NDVI (0.031, $p < 0.05$) and TI-NDVI (0.196, $p < 0.05$) for the 1982-2020 period. However, not all subregions follow this greening trend. In the northern oceanic region, the trend changes for both Max-NDVI and TI-NDVI were smaller (0.007 and 0.016) than the overall trend, and for this subregion, trends were not significant. The southern oceanic region had a significant positive trend for TI-NDVI (0.185, $p < 0.01$), whereas trends for Max-NDVI were not significant. Altogether, these results indicate trends along latitudinal and oceanity gradients.

For the ArcticHubs study region in northern Finland, Sweden, and Norway + Kola Peninsula we have also analyzed MODIS data [202]. We found patterns of reduced MODIS leaf area index (LAI) for the years 2015-2018 and NDVI (2015-2021), similar to those reported above [203]. Buitenwerf et al. suggested that this decline was due to herbivory by reindeer and geometrid moths, but since this reduction is mainly found as reduced LAI of trees (canopies) in spruce and pine forests, herbivory by reindeer and moths cannot be the cause of declining LAI; see treatment above of potential forestry impacts.

Using MODIS for the period 2000-2021, we estimated the trends of Maximum NDVI (Max-NDVI), and summed NDVI for the different hubs over the DOY [204] period 145-241. All hubs showed increasing trends of Maximum NDVI and Summed NDVI for the period 2000-2021, albeit trends for some of the hubs were not significant (Supporting information 1, Chapter 7.1).

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[202] See Chapter 2 for description of methodology

[203] Buitenwerf et al. 2018, Chen et al. 2019

[204] DOY = day of year (1 January = Day 1).

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The hubs Inari and Kovdor showed the highest increase in summed NDVI over the DOY period 145-241. Inari is shown in Figure 4.1, as an example.

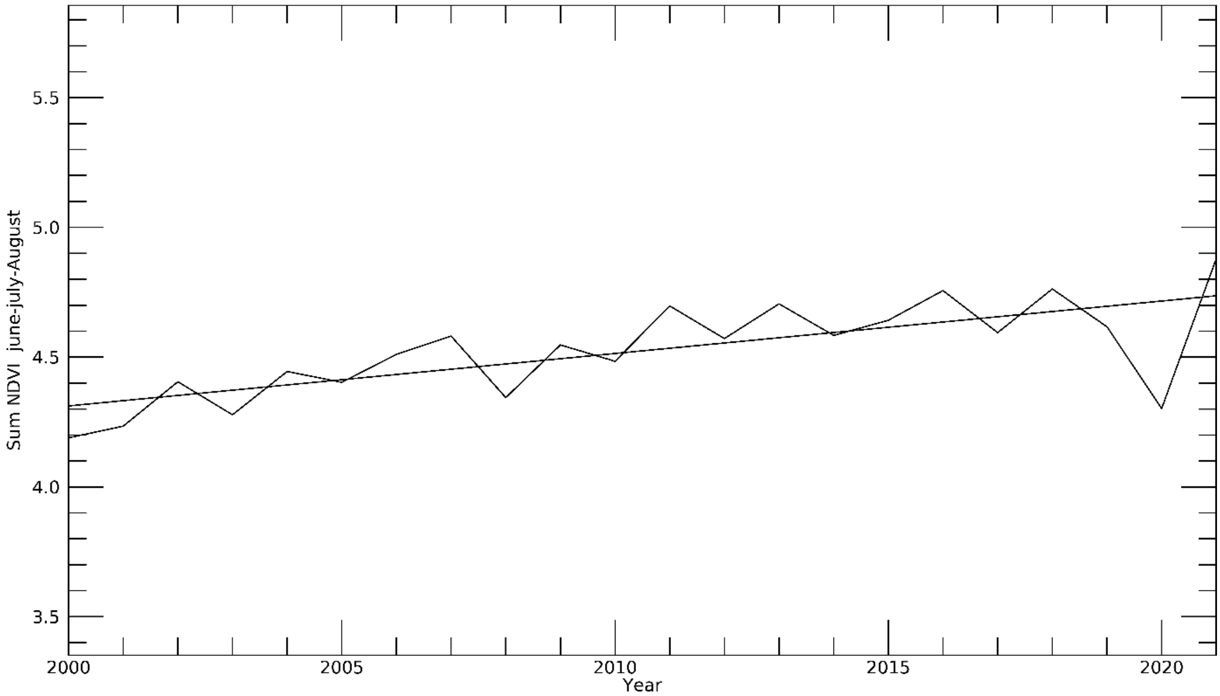

Figure 4.1. June-August summed NDVI in Inari for the period 2000-2021. Trend = 0.445 (i.e., average increase of 0.020 per year), $p < 0.01$. The year 2020 deviated largely from the overall trend.

4.1.1.3 NDVI trends in Svalbard

For the Svalbard Hub, the time-integrated NDVI (TI-NDVI) from onset of growth to time of peak (OP-NDVI) showed high correlation with plant productivity measurements in the field [205]. Our own analysis for the Longyearbyen area shows that the OP NDVI increased with about 20 % during the last 22 years. OP NDVI during this study period correlated well with mean July temperature ($p < 0.001$, $r^2 = 0.40$, $n = 22$). On average, for the entire Svalbard archipelago, the linear trend for onset of growth for the 2000 to 2020-period is 12 days earlier onset (0.57 days per year). However, there are regional differences. On the west coast, and for parts of the island Edgeøya, there is a trend of more than two weeks earlier onset, and most of these linear trends is also significant ($p < 0.05$). Slightly slower advance in onset of growth (around 7 days) were detected for the large valleys (Adventdalen, Reindalen and Colesdalen) on Nordenskiöld Land. For the Longyearbyen area, the onset of growth occurs about 8 days earlier at present as

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[205] Karlsen et al. 2018

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compared to 21 years ago. This linear trend is close to significant ($p = 0.056$). The correlation between mean June temperature and onset of growth in Longyearbyen is high and significant ($p = 0.02$, $r^2 = 0.25$, $n = 21$). For the last day with snow cover in spring in the Longyearbyen area, the MODIS data shows a weak and non-significant advance of 3 days for the 2000-2020 period. Time-integrated NDVI from onset of growth to time of peak NDVI (OP NDVI) is strongly correlated with field-measured plant productivity [206]. OP NDVI in Longyearbyen area has increased by ca. 20 % during this 21-year period. OP NDVI is well correlated with mean July temperature ($p < 0.001$, $r^2 = 0.40$, $n = 22$). The end of the growing season, which is identified remotely through the initiation of autumn yellowing, has advanced with ca. 3 days over the 2000-2020 period. Hence, the length of the growing season in the Longyearbyen area has only slightly increased during this period. This is in line with other arctic research, showing that an earlier onset of growth in spring leads to an earlier cessation of growth in autumn [207]; see section 3.1.3 for a description of this phenomenon.

4.1.1.4 NDVI trends in Iceland

The overall mean MODIS NDVI for Iceland based on the entire 22-year time series (2000-2021) of MODIS is 0.37. Figure 4.2 shows the overall mean NDVI for each pixel. Low NDVI values are displayed in red, and high values are in green. Unsurprisingly, the Central Highlands and other alpine regions show lower NDVI values (the lowest value being -0.14, which indicates no vegetation cover), and the lowland areas show higher values (the highest being 0.83, which indicate high photosynthetic activity and dense vegetation cover, or agricultural fields).

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[206] Karlsen et al. 2018

[207] Zona et al. 2022

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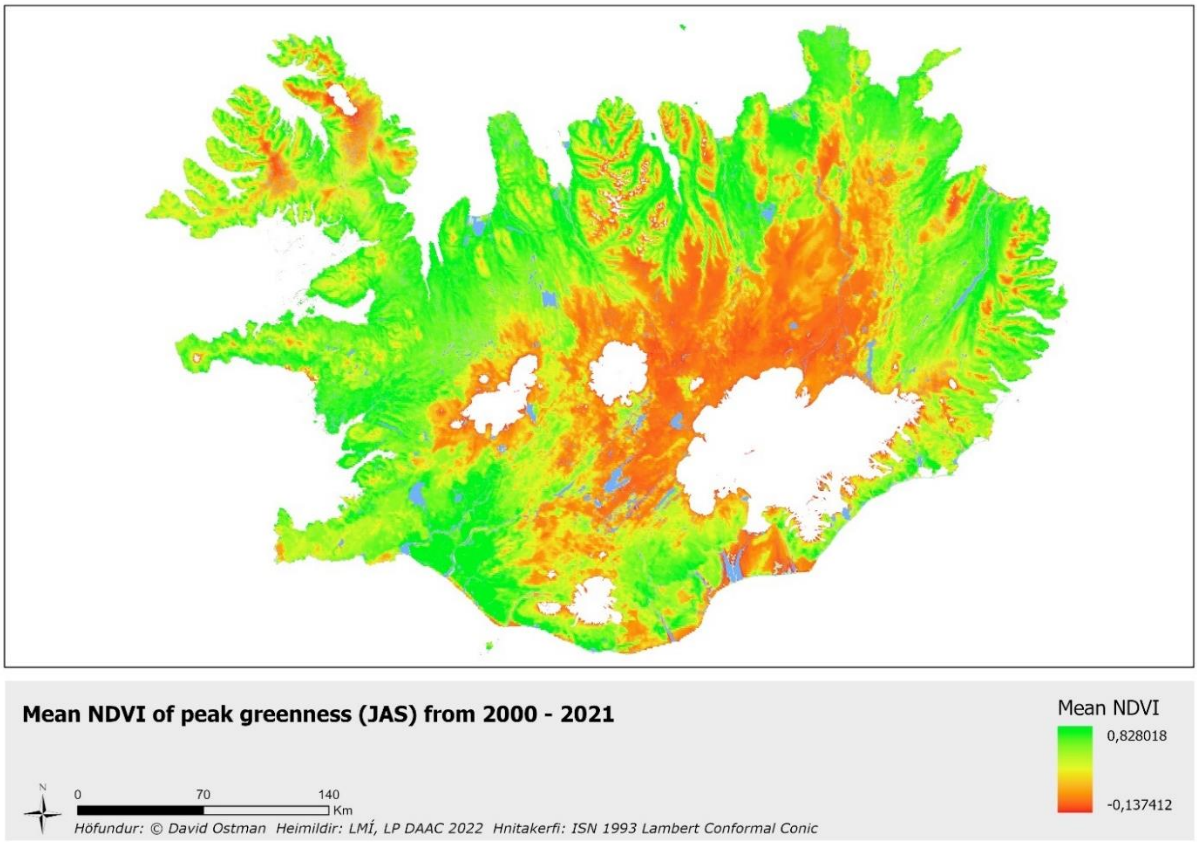

Figure 4.2. Overall mean NDVI for Iceland (2000-2021) for the months July, August, and September.

The results for the MODIS-based NDVI trend, as expressed in units per year, are shown in Figure 4.3. The analysis indicates an overall slightly positive trend with a mean change of 0.002 NDVI units per year (i.e., 0.2 % yearly increase). The standard deviation is also 0.002. The map shows the greatest negative trends in the more mountainous regions, particularly in the Tröllaskagi peninsula, and around Eyjafjallajökull, which may at least partially correlate with the ash deposition from the 2010 eruptions. There are also some slightly negative trends in parts of the lowlands. A positive trend is particularly noteworthy in many areas around the sand plains in the south as well as around the glacier margins, where a dynamic and evolving ecosystem caused by receding glaciers likely accounts for this NDVI increase.

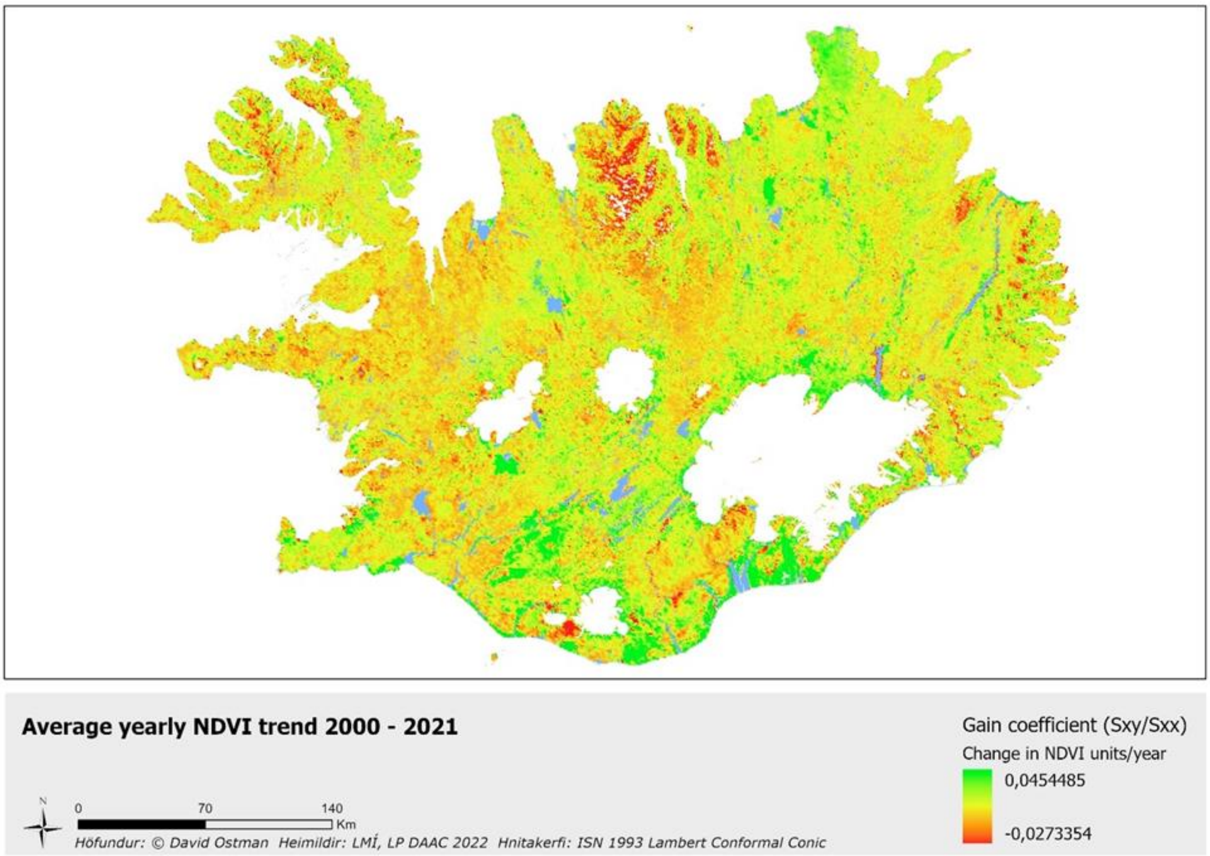

Figure 4.3. Average yearly NDVI trend (2000-2021) expressed as change in NDVI units per year.

The bar graphs in Supporting information section 7.2 show the results of the zonal statistics calculated for the gain coefficient based on region. The south-eastern (SE) region has the highest, positive mean change with 0.0040 NDVI units/year, followed closely by the southwestern region (SW) with 0.0037 units/year.

4.1.2 Species distribution change on land

It is generally a complex task to elucidate the drivers of changes in species range boundaries. Numerous non-climatic factors are involved in the shaping of species distribution ranges, but climate change is becoming a dominant factor – especially for poleward and upward range

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shifts [208]. Still, there is extremely large variation in the rates at which the range boundaries of individual species are moving [209].

Red Lists of species and habitats document which environmental pressures that have had the strongest impact on nature and biodiversity in recent decades. The evaluations of the 2021 Red List expert committee of Norway show that 89 % of all red-listed species in the country were threatened by human use of land areas, rivers, lakes, and marine waters [210]. The committee's evaluation is that climate change is the sole factor, or one of the factors, for red-list status for 8.6 % of all species in the Red List. These numbers largely reflect the global assessments of major threats to biodiversity, which, according to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), are land use, harvesting, climate change, pollution, and alien species [211].

A unique analysis of a nationwide Finnish dataset on a total of 1,478 species of birds, mammals, butterflies, moths, plants and phytoplankton, covering the years from 1978 to 2017, shows how species distributions respond to temperature, precipitation, snow cover and the North Atlantic Oscillation [212]. They found that while species turnover among decades was limited, the relative position of species within their climatic niche shifted substantially, and that a greater proportion of species responded to climatic change at higher latitudes, where changes were stronger. While the editorial commentary published in the same issue purports that this Finnish study considered underlying (non-climatic) variation in factors such as land use [213], this was not clear from the article itself. The article does not describe any non-climatic factors that are widely known to impact biodiversity in Finland, such as forestry, and other types of land use, and eutrophication [214]. Instead, the study applies spatial latent variables, which can account for the spatial autocorrelation that may arise from, for example, environmental covariates left unmeasured. The authors thus conclude that "further explicit analyses are needed to understand the combined effects and potential interactions between climate and land-use changes". The potential interactions between climate and land-use changes, including legacy effects [215], will be discussed further in the next section 4.1.2.1.

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[208] Thomas 2010, Sonntag & Fourcade 2022
[209] MacLean & Beissinger 2017, Platts et al. 2019
[210] Artsdatabanken 2021b
[211] Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services 2019
[212] Antão et al. 2022
[213] Wilson 2022
[214] Rankinen et al. 2018, Venäläinen et al. 2020
[215] Rankinen et al. 2018, Venäläinen et al. 2020

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4.1.2.1 Vegetation

It has been purported that the accelerated increase in plant species richness on mountain summits in Europe is a response to climate warming [216]. However, this study did not provide any direct evidence of a temperature-induced increase in plant species richness. While increase in plant diversity from the late 19th century until the early 21st century took place during a period of warming, this was not the only environmental parameter that changed during this time interval. Alpine and other remote natural areas have until recently been widely applied as summer grazing ranges for domestic animals, i.e., sheep, goat, cattle, and horses, while in a few regions, for example the Faroe Islands, Iceland, and parts of Norway, this practice is still prevailing [217].

The modernization and industrialization of European agriculture has reduced the need for extensive use of alpine and other remote areas as summer pastures [218]. This process, which has been termed *land abandonment*, has facilitated a rapid increase in plant biomass, including woody successions, at both low and high altitudes [219]. In Norway, domestic sheep is still abundant in the seminatural (non-cultivated) landscapes around farms, while domestic goat has almost disappeared from the Norwegian agricultural landscape. The number of goats today is only 18 % of the maximum, which occurred in the 1930s [220]. For hundreds of years, goats were roaming freely in the Norwegian landscape, normally above the timberline (Figure 4.4). As goats are good climbers, they reach to the highest mountain peaks. Nowadays, the rapidly regrowing cultural landscapes near farms offer sufficient forage, so viewing goats in the alpine landscape is now a rare event. Goat is an excellent browser – as opposed to sheep, which is a grazer. While grazers primarily feed on grass and other lower vegetation, browsers feed on any vegetation, even woody stems of shrubs and trees, and remove large parts of the vegetation. Hence, a mountain landscape shaped by decades of extensive goat browsing has a very barren appearance, and release of goat browsing pressure has a rapid and massive impact, affecting both biomass and biodiversity from seashore to the highest peaks [221]. Thus, explaining increasing alpine biodiversity over the last 100-year period is fully possible even without placing it in a climate change context.

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[216] Steinbauer et al. 2018
[217] Ross et al. 2016
[218] Nettier et al. 201, Hinojosa et al. 2016, Hohensinner et al. 2021
[219] Cramer et al. 2008, Ustaoglu & Collier 2018, Foucher et al. 2019, Hannon GE et al. 2020
[220] Bårdløkken 2014, Statistics Norway 2022
[221] Kala et al. 2002, Wehn et al. 2011, Potthoff 2017, Garcés-Pastor et al. 2021, Mienna et al. 2022

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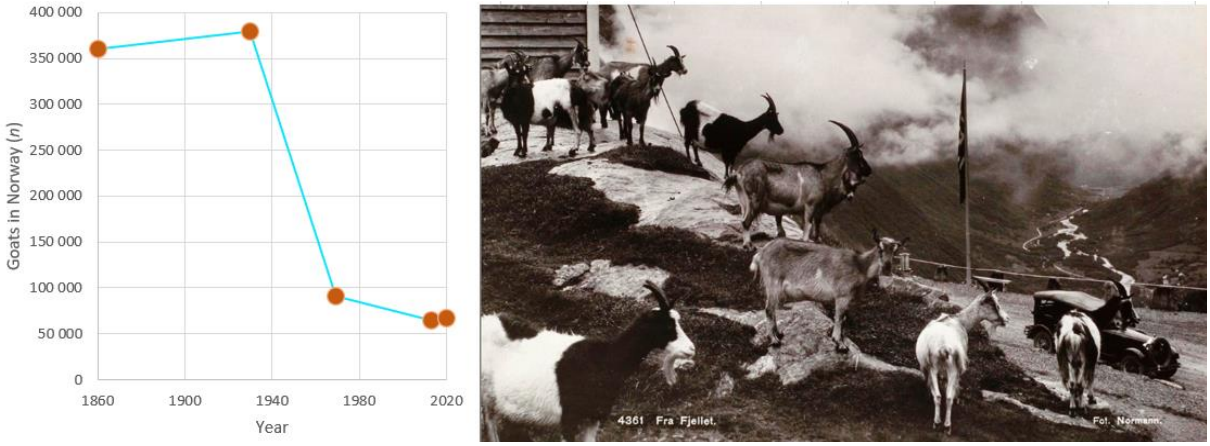

Figure 4.4. Goats in Norway 1860-2020. See text for source. The photograph is a reproduction of a postcard from a mountain pass in western Norway (Normanns kunstforlag A/S) [222]. Year unknown, but probably from the 1920s. Disclaimer: Before this photo is reproduced in any public report, permission must be applied.

These types of culturally induced changes have indeed taken place in many of the focal sites in ArcticHubs. For Finnmark in northernmost Norway (including the hubs Kvalsund-Kautokeino and Varangerfjorden), a multifactorial assessment of forest fluctuations over a 100-year period (1910-2015) concluded that human activities (logging and regulation of the abundance of domestic herbivores, i.e., goat, sheep, cattle – and semi-domestic herbivores, i.e., reindeer) were the primary drivers of fluctuating forest cover [223]. In fact, the most rapid increase in deciduous forest establishment took place during a period of slight summer cooling. A similar forest expansion during a period without any temperature increase has taken place at Kola Peninsula [224]. Similar legacies of historical human activities affect woody plant dynamics throughout the Arctic [225]. Normand et al. [226] strongly advocate that one first must explore the recent and longer-term impacts of human activities such as hunting, herding, fire, extraction, and agriculture. Only by knowing these impacts, one can assess if there are any unequivocal impacts of climate change on recent vegetation dynamics.

Thus, since the use of the cultural landscape has been reduced so dramatically during the last 50-100 years, it is not straightforward to state with confidence that any latitudinal or altitudinal range expansion of plant species are primarily due to warming. An additional complicating

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[222] Statistics retrieved from Statistics Norway 2022; image retrieved from Nordmøre museum 2021
[223] Tømmervik et al. 2019
[224] Mathisen et al. 2014
[225] Hofgaard et al. 2013, Løkken et al. 2019, Eide et al. 2021, Harr et al. 2021, Stark et al. 2021
[226] Normand et al. 2017

factor is that climatic change is not purely stimulatory to plant growth. The cold seasons have been warming more than the growing season, resulting in disturbance of hibernation in plants and often leading to large-scale visible damage (see sections 3.2 and 4.2).

Climate change is not only about temperature. Some areas are becoming drier, but all hubs of the ArcticHubs study region are becoming wetter; see Chapter 3. Increasing humidity has contrasting impacts on potential species distribution range than warming. Some of the drier regions of the Nordic Arctic Region have become wetter in recent decades. It has been suggested that increasing wetness is a primary reason for the local range expansion and overall increase in abundance of some vascular plants and mosses to the mountain plateau Finnmarksvidda in northernmost Norway [227]. This area received 81 % more precipitation during the period 1991-2000 as compared to the period 1931-1960. The short shrub bilberry (*Vaccinium myrtillus*), the herbs dwarf cornel (*Chamaepericlymenum suecicum*) and arctic starflower (*Lysimachia europaea*), and the mosses splendid feathermoss (*Hylocomium splendens*), and red-stemmed feathermoss (*Pleurozium schreberi*) were among the plants that increased in abundance during this period. The increase of these plants is also possible to explain by non-climatic factors, especially increasing reindeer grazing pressure that led to reduced abundance of landscape-wide mat-forming lichens, facilitating the expansion of vascular plants and mosses. The most plausible explanation in this case is that the increase of plants was a combination of changes in humidity and grazing pressure.

Regarding warming within the ArcticHubs region, some of the more obvious vegetation responses are taking place in alpine areas where glaciers and snowbeds are declining due to longer and warmer summers [228]. Retreating glaciers facilitate short-distance dispersal of pioneer organisms, mainly consisting of high-alpine lichens, bryophytes, and a small selection of vascular plants, to recently deglaciated terrain [229]. Snowbeds (Figure 4.5), palsa mires and other snow-and-ice-dependent habitat types are therefore considered as threatened (see further treatment in section 4.1.4). Many species preferring snowbeds and other snow-related habitats are also threatened. For example, *Phippsia algida*, commonly known as ‘ice grass’ or ‘snow grass’, is considered as threatened (VU) in Finland, Norway, and Sweden, and as near threatened (NT) on Svalbard [230]. While the red list status of this species in these countries

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[227] Tømmervik et al. 2004
[228] Janssen et al. 2016, Cauvy-Faunie & Dangles 2019, Moon et al. 2021, Taveirne et al. 2021
[229] Fremstad 1997, Cauvy-Faunie & Dangles 2019, Losapio et al. 2021, Fryday & Dillman 2022
[230] Hyvärinen et al. 2019, Eide et al. 2020, Artsdatabanken 2021

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primarily relies on expected decline soon, *P. algida* already suffers from combined temperature- and drought-induced population reduction at some alpine sites [231].

Figure 4.5. An arctic-alpine snowbed landscape, Seiland National Park, Finnmark, Norway. The glacier Seilandsjøkelen in the background. Photo: Karl-Otto Jacobsen ©, Norwegian Institute for Nature Research.

Most vascular plants on the Icelandic Red List of species are threatened by non-climatic factors [232]. Most species on this Red List have very few populations with few individuals in each population. One of these species is the leafy saxifrage *Micranthes foliolosa*, which grows in upland, alpine areas of northern Iceland, with a preference for snowbeds. The Red List states that it is threatened (VU) because of a restricted distribution range in a habitat that will change rapidly with increasing impacts of climate change. Thus, although not stated explicitly, it seems that (future) climate warming is the primary reason for the red listing of this species in Iceland.

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[231] Sandvik & Odland 2014

[232] Icelandic Institute of Natural History 2018

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4.1.2.2 Animals

Animals generally migrate faster than plants. Thus, range shifts or range expansions linked to climate change are more widely observed in certain groups of animals than in plants. Some birds breeding in boreal and arctic environments show population increase and expansion of breeding area. This includes several species of waders, geese, and swans. Earlier onset of spring, wetter conditions and longer snow-free period in autumn are considered as primary reasons for this increase. These climatic changes have resulted in, for example, earlier onset of plant growth, improved forage resources, more snow-free space for nesting, and a longer snow-free period after nesting increasing the fledging probability of chicks. However, non-climatic factors also contribute to increasing trends for these species, for example reduced hunting pressure, and increasing abundance of waste grains on agricultural fields at spring stopover sites [233], and it is generally a cumbersome task to differentiate the relative importance of climatic vs. non-climatic factors for population increase. Overall, most bird species in the Nordic region show stable population trends [234]. On the other hand, grouse species may suffer from the asymmetric spring warming [235]. As willow grouse is a keystone species in the arctic and alpine regions (similar to the keystone role of lemming), declining population sizes will have ecosystem-scale impacts.

For sea birds, see section 4.1.3.

Invertebrates are another group showing expanding distribution ranges. Here, we discuss some examples of expanding invertebrates. Within the ArcticHubs study region, among the most unwanted expansions is the increasing abundance and distribution of ticks, especially of the castor bean tick (*Ixodes ricinus*) that suck blood from mammals including humans [236]. This has led to an increase in the tick-borne diseases Lyme disease (borreliosis) and encephalitis (TBE) in humans in the Nordic countries and elsewhere. While it generally has been assumed that climate change is a primary driver of increasing tick abundance and distribution ranges [237], a recent study suggests that human-induced land cover change is the primary driver, as it has resulted in increased habitat suitability for ticks [238]. For the distribution of Lyme borreliosis, this study shows that last year’s summer temperature is a controlling factor. Thus, the increase

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[233] Jensen et al. 2014, Shimmings & Øien 2015, Simonsen et al. 2016, Fox & Madsen 2017, Lefebvre et al. 2017, Lindström et al. 2019, Tombre et al. 2019, Doyle et al. 2020, 2021, Layton-Matthews et al. 2020, Stokke et al. 2021a, Heldbjerg et al. 2022
[234] Lindström et al. 2019
[235] Ludwig et al. 2006
[236] Talleklint & Jaenson 1998, Jore et al. 2011
[237] Jore et al. 2014, Laaksonen et al. 2017, Hvidsten et al. 2020, De Pelsmaeker et al. 2021
[238] Leibovici et al. 2021

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of ticks and tick-borne diseases is a result of a combination of landscape change and climate change. Cervids (moose, red deer, roe deer) are hosts for ticks. Stigum et al. [239] conclude that an overall extensive population increase of cervids in northern Europe, including Norway, Sweden, and Finland, have contributed to the expansion of ticks and to increasing infestation rates of domestic sheep with tick-borne diseases. It does not mean that all species of cervids show increasing trends in all countries. For example, in Sweden, the post-hunt moose abundance decreased by 15 % from 2012 to 2020 [240].

Outbreaks of geometrid moths occur on regular intervals within the study area, especially in the Nordic downy birch (*Betula pubescens*) forests. Geometrid moths, in particular winter moth (*Operophtera brumata*), have extended their distribution range northwards [241]. Winter moth is even expanding into shrub tundra in the Nordic Arctic Region [242]. The dominating theory is that climate warming is the cause for these expansions, primarily due to increased winter survival of eggs from fewer winters with lethally cold temperature, i.e., periods with temperature below ca. −36 °C [243]. In Greenland, the noctuid moth *Eurois occulta* has outbreaks at regular intervals feeding on green plants in such extent that outbreaks are easily visible as brown, leafless patches in the landscape. However, data are currently not sufficient to verify any climate-induced increase in range of this species [244].

Yet another invertebrate pest that is expanding rapidly in northern regions is the deer ked, also called deer fly (*Lipoptena cervi*). It sucks blood from cervids, especially moose, deer, and reindeer and occasionally bites humans. Its rapid expansion is primarily a result of the rapidly increasing populations of cervids and not of climate change per se [245].

Climate change may be a minor driver of increasing populations of cervids in northern Europe, for example by reduced snow depth during winter, which facilitates movement and reduces hunting pressure from lynx and other predators. However, in many northern European countries, moose and red deer were at the brink of extinction during the 19th century due to overexploitation. Reduced human hunting and cessation of traditional agricultural practices (see treatment above) are therefore considered as the most important factors for the massively

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[239] Stigum et al. 2019
[240] Kalén et al. 2022
[241] Jepsen et al. 2016
[242] Vindstad et al. 2022
[243] Tenow et al. 1999, Callaghan et al. 2004, Neuvonen et al. 2005, Jepsen et al. 2008, 2009, Ammunét et al. 2015
[244] Lund et al. 2017
[245] Madslien et al. 2011, 2012, Mysterud et al. 2016

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increasing populations of moose, roe deer and red deer in northern Europe [246]. The increased populations of moose may have a significant effect on the number of deciduous trees in the forests [247]. Our own unpublished results from a high-density moose area (Pomokaira, Sodankylä, in northern Finland) show strikingly contrasting patterns of deciduous trees – with high abundance in fenced areas and near-complete absence in unfenced areas.

Population increases for numerous terrestrial wild mammalian species other than cervids are also explained primarily as a direct effect of human impacts, especially reduced hunting pressure, increased forage resources due to reduced haymaking and reduced number of domestic animals in the wild, legacies of human-induced establishment of mammalian populations at new sites, and a generally improved environmental management in recent decades.

In alpine areas, rodents, in particular lemming, are keystone species having strong influence on lower and higher trophic levels. During lemming and vole outbreaks, vegetation is heavily grazed and turned to such extent that the area of outbreak is easily identified by satellites monitoring vegetation greenness [248]. It takes many years for vegetation to recover to previous states after such outbreaks. Rodents are also important food resource for birds and the arctic fox. Lemming is closely dependent on snowbed habitats, as most winter nests for lemming are found in snowbeds [249]. As warmer winters lead to increasing disturbance to the snowpacks in snowbeds, this has devastating impacts on winter survival of lemming [250]. Also, non-snowbed overwintering populations of small rodents are severely affected by ongoing changes to the snowpack [251]. Thus, the state of small rodent populations is evaluated to be low at least in Norwegian alpine areas [252]. Nevertheless, lemming and alpine voles are considered as least concern (LC) by the Red List expert committees in all the Nordic countries. After a period with rather few outbreaks, in recent years, lemming has had several large outbreaks in Scandinavian mountains.

The arctic fox (*Vulpes lagopus*; see photo on p. 9) is one of the predators that is largely dependent on small rodents. It is threatened in Finland (Critically endangered – CR), Sweden (Endangered – EN), Norway (EN), but not in Iceland and Svalbard (Least concern – LC). Extensive hunting and poisoning led it to the brink of extinction, and it was in need of total

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[246] Jakobsson & Pedersen 2020, Månsson et al. 2021, Norwegian Environmental Agency 2022
[247] Månson et al. 2007, Kolstad et al. 2018
[248] Olofsson et al. 2012, 2013
[249] Björk & Molau
[250] Callaghan et al. 2013
[251] Framstad 2014
[252] Jakobsson & Pedersen 2020

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protection. It was protected in Finland, Sweden, and Norway between 1930 and 1940, but it did not immediately respond with increasing populations. Breeding programmes have helped expanding the population, which, in Norway, has resulted in an improvement of the Red List status – from CR in 2015 to EN in 2021. Still, recent climate change is assumed to have had a negative impact on the arctic fox, primarily by dampening the outbreaks of its most important food resource, namely small rodents (see treatment above). In Finland, the arctic fox has not had successful breeding for more than 20 years, until a recent successful denning was observed in northernmost Finland in July 2022 [253]. The Nordic Red List committees expect that climate change will have stronger negative impacts on the arctic fox during the next decades.

From the high-Arctic regions of the study area, we provide some examples from Svalbard and Greenland. The polar bear (*Ursus marinus*) is a global symbol of climate change. The species is found within two of the hubs in this project, namely Svalbard and Nuup Kangerlua. In both places, the polar bear is considered as being Vulnerable (VU) [254]. While hunting was the main regulatory factor for a long time, reduced sea ice due to arctic warming is having increasing impact on polar bear. The population on Svalbard has been stable, but it is on the Red List primarily in accordance with the D1 criterion, meaning very few reproductive (< 1,000) individuals. In Greenland, it is red-listed based on criterion A3c, meaning an expected reduction over the next ten years or three generations caused by shrinking distribution area and/or reduced habitat quality, and this is linked to reduced sea ice.

Arctic wild reindeer is of Least Concern (LC) both in Svalbard and Greenland, except for the subspecies East Greenland caribou (*Rangifer tarandus eogroenlandicus*) which has been extinct (Ex) in Greenland since 1900. Despite the fact that Svalbard reindeer (*Rangifer tarandus platyrhynchus*) suffer from high mortality in some winters, the population has grown from ca. 1,500 animals in 1958 to ca. 22,435 animals in 2018 [255]. Unregulated hunting was the main cause of the very low population in 1958. The population was probably even lower at the time of protection. It has been protected since 1925. Svalbard reindeer (Figure 4.6) has until recently had no natural enemies. However, it has been documented that some polar bear individuals have specialized in reindeer hunting [256]. Their shift to a more terrestrial diet is linked to climate change; as it is a response to reduced sea ice, and hence, reduced capability to hunt seals. While threats from future climate change is considered in the red-list evaluations of numerous other species in Svalbard, the ongoing and future climate change impacts is not explicitly mentioned

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[253] Viinikka 2022
[254] Boertman & Bay 2018, Eldegard et al. 2021
[255] Le Moullec et al. 2019
[256] Derocher et al. 2000, Stempniewicz et al. 2021

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for Svalbard reindeer in the Red List for Svalbard [257], which is surprising given the rapid ongoing climate change on the archipelago.

To summarize, this overview (section 4.1.2 including both subsections) of changes in species distributions on land underlines the complexity of terrestrial ecosystems; changes are the result of numerous internal and external drivers, pressures and stressors, of which climate change is only one of many factors. Impacts of climate change on species distributions are most evident in the high-Arctic, while climate change impacts are more elusive towards more populated regions where historical and current land use practices largely confound or mask climate change impacts.

4.1.3 Marine species distribution change

Harvesting, environmental pollution and other human activities do indeed affect life in the seas. Despite this, the impacts of climate change are more evident on distribution of species in the marine ecosystems than in terrestrial ecosystems of the ArcticHubs region. Despite anomalously cool sea surface temperature during summer 2021 in parts of the ArcticHubs study region (Norwegian Sea, Barents Sea, Bothnia Bay, Baffin Bay, Davis Strait – but not western North Atlantic), there is a strong warming trend of northern seas. Linear trends for the period 1982-2021 show significant warming of up to 0.1 °C per year within the ArcticHubs study region. The warming is closely linked to declining sea ice [258].

Several Atlantic fish species are migrating northwards. One such example is the Atlantic mackerel (*Scomber scombrus*), which was recorded in Isfjorden on Svalbard in September 2013. This was the first record of this species in Svalbard seas [259]. This represented a rapid northward expansion of ca. 5 latitudinal degrees of this species’ distributional range. Atlantic mackerel has in recent years also become more common around the Faroe Islands and Iceland and has even been caught in the waters east of Greenland. Mackerel can swim fast over extended periods. Hence, it can quickly adopt to warmer waters. During a period of only eight years (2006-2013), six new species of fish were recorded in Svalbard waters. The first year in this period, 2006, had anomalously warm sea temperature, and during this year three of the six new species were recorded. These three species were capelin (*Mallotus villosus*), haddock (*Melanogrammus aeglefinus*), and snake pipefish (*Entelurus aequoreus*). Later, cod (*Gadus morhua*) and Atlantic herring (*Caprea harengus*) were recorded in 2008 and 2012, respectively.

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[257] Eldegard et al. 2021e
[258] Lind et al. 2018
[259] Berge et al. 2015

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Similar warming impacts on fish communities are recorded elsewhere at high northern latitudes. Previously characterized by arctic fish communities, the Barents Sea is becoming dominated by boreal fish species [260]. Even deep demersal fish communities down to 1000-m depth are changing as a response to warming seas, a study from East Greenland shows [261]. As a result of shorter ice season, Atlantic cod has recently migrated into the historically ice-rich Ilulissat Icefjord on the northwestern part of Greenland [262].

Warmer sea water has also promoted range extensions by Arctic benthos. This took place during the early 20th century warming period of the eastern North Atlantic, and it is occurring once again during the current warming trend [263].

For a pelagic species like mackerel, changing sea temperature may thus expand or contract its distributional area. Demersal species like cod (*Gadus morhua*), in contrast, are more locked to smaller areas and tend to be split into separate stocks within these areas. If environmental conditions in one of these areas become too challenging, the entire stock in this area may perish. For cod, the temperature at the time of spawning is a critical constraint since too warm waters may prevent successful spawning. This is a matter of concern for the two cod stocks inhabiting Faroese waters, since these waters are already close to the upper tolerance range for the temperature at the time of spawning in spring. The exceptional warming during the early years of the 21st century has been suggested as one possible cause of a long-term decline of the Faroe Bank cod stock [264]. Another potential negative impact of sea temperature increase in Faroese waters is its effect on the overwintering phase of sand eel (*Ammodytes* spp.; also known as sand lance). This species group is a key link between lower trophic levels and commercially important fish stocks (e.g., cod) as well as sea birds. During winter, sand eel remains buried in the sediment, relying on stored fat reserves and these reserves have been found to decrease with increasing winter temperature [265]. Increasing sea temperature during winter and spring may thus have both direct and indirect negative impacts on fish species of great importance for the Faroese hub.

The poleward migration of benthos and fish strongly influences sea birds that are reliant on fish. Several previously highly populated sea bird hotspots in Iceland and Norway have become abandoned, and some bird colonies have moved into urban areas [266]. The world's largest colony

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[260] Fossheim et al. 2015, Frainer et al. 2017
[261] Emblemsvag et al. 2022
[262] Schiøtt et al. 2022
[263] Drinkwater 2006, Renaud et al. 2015, Csapó et al. 2021
[264] Steingrund 2019
[265] Eliasen et al. 2011, Eliasen 2013
[266] Anker-Nilsen et al. 2021

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of Atlantic puffin (*Fratercula arctica*) in Iceland has recently experienced a strong decline. A recent study revealed strong negative correlations between puffin productivity and sea surface temperature [267]. A study from 2015 on Norwegian seabirds suggest that there are two main reasons for the declining or collapsing seabird populations. There is increased predation in the seabird colonies from avian and mammalian predators, and ecosystem changes are affecting the availability of prey [268]. As shown in the previous paragraphs, warming seas are an important factor for these ecosystem changes to prey.

However, increasing populations of avian and mammalian predators may primarily be a result of wildlife management. For example, the population of white-tailed eagle (*Haliaeetus albicilla*) in the Nordic countries has increased substantially during the most recent 20-year period, primarily due to reduced killing by humans [269]. White-tailed eagle is, along with great black-backed gull (*Larus marinus*) and raven (*Corvus corax*) the fiercest avian predators of sea bird chicks in cliffs.

Sea birds searching for food along the ice margin are more directly impacted by climate change and its impacts of reduced sea ice. The ivory gull (*Pagophila eburnea*) is one example. It is Vulnerable (VU) in both Svalbard and Greenland. The Svalbard-breeding population has shown a 40 % decline over a short period (2009-2019) [270].

High-Arctic marine mammals are also threatened by warmer waters and declining sea ice extent. Ringed seal (*Pusa hispida*) is a signature species of the arctic sea ice, as it is the only seal in the European Arctic that can maintain breathing holes through thick ice. While it is of Least Concern (LC) in Greenland, it is Vulnerable (VU) in Svalbard due to the retreating sea ice; the sea ice season in the northern Barents Sea has been reduced by 20 weeks during the most recent decades [271]. Ringed seal also lives in Bothnia Bay and the Finnish Lake Saimaa where the seal takes advantage of the snow-covered ice that develops every winter. The Bothnian population (ssp. *botnica*) is considered as being of Least Concern (LC) on the Swedish side and as being Near Threatened (NT) on the Finnish side, while the freshwater population in Lake Saimaa (ssp. *saimensis*) is considered as Endangered (EN) [272]. Climate change is one of several factors for the red listing of the Finnish populations.

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[267] Hansen et al. 2021
[268] Fauchald et al. 2015
[269] Hyvärinen et al. 2017, Staneva & Burfield 2017, Moeslund et al. 2019, Eide et al. 2020, Eskildsen et al. 2020, Green et al. 2020, Artsdatabanken 2021
[270] Stokke et al. 2021b
[271] Laidre et al. 2015, Eldegard et al. 2021a
[272] Hyvärinen et al. 2019, Eide et al. 2020

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The Greenland right whale (*Balaena mysticetus*, also known as bowhead whale and Arctic whale) can break through thick sea ice. It feeds on the rich zooplankton communities that develop in arctic waters. Hunting nearly brought this species to extinction. The North Atlantic population is considered as EN (Svalbard) and VU (East Greenland) [273]. These high Red List statuses are not only due to historic hunting; the species is expected to respond negatively to warmer oceans and reduced sea ice. Increased marine noise is another stressor that is expected to increase with increasing arctic marine shipping.

The narwhal (*Monodon monoceros*) is another iconic arctic whale associated with sea ice. It spends the whole life in drift ice and prefers waters with up to 90 % ice cover [274]. The small Svalbard population is considered as VU, while the much larger Greenland populations are considered as EN [275]. Like the Greenland right whale, narwhal is expected to respond negatively to warmer oceans, reduced sea ice and increasing marine noise.

The harbour seal (*Phoca vitulina*) is a widespread temperate-to-arctic species that is expected to expand northwards and increase its population size with ongoing arctic warming. In Svalbard, it is expanding, but since its population size is still below 2,000 individuals it is considered as Near Threatened (NT) [276]. In Greenland, the harbour seal was hunted almost to extinction, but is now protected by law. It is considered as Critically Endangered (CR), but there is expectance that the population will increase, and that the species will benefit from climate warming [277]. The Icelandic population of harbour seal declined by 72 % from 1980 to 2018 and is considered as critically endangered (CR). The main reasons for this decline were traditional hunting, by-catches in fish nets, and derogation hunting to protect salmon populations entering rivers [278]. Seal hunting is now illegal in Iceland, and a special permit is required before any hunting can be undertaken. It is less likely that the Icelandic population will respond positively to the ongoing warming, as Icelandic waters for centuries have had the ideal temperature conditions for this species.

Overall, we can conclude that a massive biodiversity change caused by warming seawaters is ongoing, and this change will be even more pronounced as the northern seas become even warmer. Increased application of species monitoring, environmental management, and protective measures will be required to dampen the negative effects of ocean warming.

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[273] Boertmann & Bay 2018, Eldegard et al. 2021b
[274] Ahonen et al. 2019
[275] Boertmann & Bay 2018, Eldegard et al. 2021c
[276] Eldegard et al. 2021d
[277] Rosving-Asvid 2010, Boertmann & Bay 2018
[278] Icelandic Institute of Natural History 2018

4.1.4 Terrestrial and marine habitat and ecosystem change

Species and their ecosystems are under constant change from a concert of external pressures. As shown above, climate change is only one of numerous factors causing changes to species and ecosystems.

The expert committee for threatened habitat types in Finland concludes that recent climatic change (to 2018) has had only minor impact on Finnish habitat types [279]. The most important factors for habitats being threatened are forestry, drainage, clearing of areas for arable land, construction, and eutrophication. The only exception is the northern Finnish fell region, i.e., upland habitats in northern Finland mostly above the climatic limit for forest growth, but also including mountain birch forest with scattered stands of Scots pine, spruce, and aspen. Thirty-one fell habitats were considered as threatened by climate change, ten of these with high significance, twelve with “rather high significance” and the remaining nine with “rather low significance”. The habitats adversely affected by climate change are all restricted to snowbeds, snow patches and permafrost soil and peat. This includes the palsa mires, which have a core of permafrost that leads to a dome-shaped or plateau-shaped structures in wetlands.

The Swedish assessment of threats to habitats and species concludes nearly identically as the Finnish assessment; in Sweden agriculture, forestry, and exploitation of lands for infrastructure are the main threats to habitats [280]. These factors are a threat to ca. 48 %, 32 % and 21 %, respectively, of the total number of threatened habitats. In comparison, climate change is considered a threat to ca. 6 % of all threatened habitats. As in Finland, the habitats considered threatened by climate change are primarily restricted to the alpine zone.

The expert committee for threatened habitat types in Norway concluded in 2018 that climate change is one of the factors leading to red list status for a total of 72 habitat types, i.e., 25 % of all red-listed habitat types [281]. The expert committee’s evaluation is that temperature is by far the most important climate change element for habitat reduction. It is affecting, or will affect, 56 of these 72 habitat types. The second most important factor is prolonged growing season, affecting 15 habitat types. “Slow, but significant reduction” is by far the most widely used term for describing the impact of climate change. Only for one habitat, the term “rapid reduction in area” was applied. This was for a shallow marine habitat dominated by sugar kelp (*Saccharinia*

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[279] Kontula & Raunio 2019
[280] Westling et al. 2020
[281] Artsdatabanken 2018

latissima), which has experienced a severe reduction over a 50-year period [282]. This habitat is found in the marine waters of the Egersund hub and elsewhere in the Skagerak and North Sea. The committee also points out that nutrient enrichment is an important factor for the kelp decline, while increasing sea water temperature may become the most important factor in the future. Thus, the term “rapid reduction” for this habitat primarily apply to the consequences of recent nutrient enrichment.

The group of Norwegian habitats threatened by a climate-induced slow, but significant reduction includes many of the same habitats as are threatened in Finland and Sweden, for example palsa mires and snowbed habitats.

These same habitats are also considered threatened by climate change according to the EU’s expert committee for threatened habitats [283]. Palsas (Figure 4.7) are specifically treated, while snowbeds are indirectly included in the habitat “snow pack”, which is considered as vulnerable (VU) in the EU Red List.

Overall, the assessment of climate change as a threat to habitat types, as expected, strongly correlate with the red lists for species; it is the coolest habitats and their species that are considered most threatened by climate change.

Figure 4.6. Svalbard reindeer (*Rangifer tarandus* ssp. *platyrhynchus*). Photo: Jarle W. Bjerke ©

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[282] Gundersen et al. 2018
[283] Janssen et al. 2016

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Figure 4.7. Thawing palsa dome near Iešjávri, along the reindeer migration route in the Kvalsund-Kautokeino hub. Photo: Jarle W. Bjerke ©

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4.2 Impacts of changing frequency of extreme weather events on ecosystems and keystone species

This section focusses on natural ecosystems and their species. While the reindeer is part of the natural ecosystems, it has become semi-domestic within the study region of ArcticHubs. Impacts on reindeer and reindeer husbandry are therefore treated in Chapter 5.

The nature of extreme events and impacts on natural ecosystems and society have recently been thoroughly reviewed [284]. This summary of impacts of changing frequency of extreme weather events on ecosystems and keystone species largely rely on recent reviews and supplement with a few additional sources.

4.2.1 Cold seasons

While extreme freezing events historically was a factor damaging natural ecosystems and limiting human expansion, extreme warm events during the cold seasons are increasing in frequency, with major impacts on nature and society. Winter is the period for hibernation for most organisms overwintering in winter-cold land areas. Warm weather events raise temperature to well above freezing, reduces and compacts the snowpack, and disturb hibernating ecosystems and their species [285]. When such warm events take place in late winter, they are often termed as “false spring” [286]. Temperature can change extremely rapidly during such events. On Svalbard (79° N), temperature during a mid-February warming event rose by 28 °C within 49 h, from −23° C to +5° C [287].

Warming events lead to complete or partial snowmelt. When temperature returns to freezing, the partially melted snow turns into a very hard and icy snowpack, or into block ice, with devastating consequences for lemming and other rodents and small invertebrates living in the subnivean space, and for mammalian herbivores (musk ox, reindeer, etc.) that are reliant on foraging on vegetation underneath the snowpack [288]. Ground-ice and hard snowpack are also detrimental to vegetation. The insulation properties of ice and hard snowpacks are much lower than within an intact snowpack, exposing subnivean organisms to near-ambient fluctuations in

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[284] Bokhorst et al. 2016, National Academies of Sciences, Engineering, and Medicine 2016, Coleman & Wernberg 2020, Walsh et al. 2020, 2022; Walsh 2021, Rixen et al. 2022
[285] Bokhorst et al. 2009, 2016, Bjerke et al. 2017a, 2017b, Williams et al. 2015, Vikhamar-Schuler et al. 2016
[286] Chamberlain et al. 2019
[287] Bjerke et al. 2017a
[288] Coulson et al. 2000, Gilg et al. 2009, Callaghan et al. 2013, Rixen et al. 2022

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temperature and light, increase mechanical damage to stems and buds, and lead to detrimental hypoxic or anoxic conditions [289]. Vegetation exposed to ice in winter and spring often show reduced greenness and productivity during the following growing season [290].

The impacts of full or partial snowmelt may last into the growing season. After a midwinter snow thaw, soils often freeze deeper and thaw out later, with the consequence that reactivated evergreen plants dry out when aboveground biomass is reactivated by the first warm weather in spring, a phenomenon known as “spring drought” [291].

As winter has been warming more than summer, and this difference in warming rates between seasons will continue, it is projected that ongoing and future changes in cold-season conditions will contribute substantially to future plant-compositional structure of northern ecosystems and future distribution change of plant functional types, partly because of cold-season extreme climatic events [292]. See section 4.3 for more information on expected future changes.

4.2.2 Warm seasons

Despite that the ArcticHubs study region generally will become wetter, there is a risk for increasing frequency of summer drought episodes; see Chapter 3.4.2. North-eastern Finland receives on average between 401 and 500 mm of annual precipitation and is hence one of the driest regions of north-western Europe. Still, there are little or no evidence of any major direct drought-induced impacts on vegetation during dry summers [293]. One major reason is that vegetation is adapted to dry conditions. Another possible reason is that large parts of the forests in Finland are managed [294]; thinned stands dominate the production forest of northern Finland, which limits drought-induced fire risk due to low amounts of deadwood. A third reason is that this region has a high density of lakes, swamps and mires that create natural obstacles for wildfire and at the same time provide water to plants even in dry periods [295]. Drought-induced damage to Finnish forests appears to decrease with increasing latitude, despite the fact that northern forests receive less rainfall than southern forests [296]. Still, a global study of summer drought identified an area in northern Finland that scored high on the Palmer Drought Index,

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[289] Kullman 1989, Crawford 1992, Crawford et al. 1994, Andrews 1996, Bjerke et al. 2015, 2018a, 2018b
[290] Bjerke 2011, Bjerke et al. 2017a, Ritz et al. 2020
[291] Kalberer et al. 2006, Bjerke et al. 2014, Hammond et al. 2019, Song et al. 2021, Treharne et al. 2020
[292] Sturm et al. 2005, Zimmermann et al. 2009, Bokhorst et al. 2015, 2016, Beigaitė et al. 2022
[293] Venäläinen et al. 2020, Korhonen et al. 2021
[294] Hallikainen et al. 2010, Lehtonen et al. 2014, Mattila et al 2016, Korhonen et al. 2021
[295] Lehtonen et al. 2014, Lindberg et al 2021
[296] Venäläinen et al. 2020

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and that this was associated with a remotely sensed decline in vegetation greenness (often called ‘browning’) over the period from 1982 to 2002, reflecting declining productivity caused by summer drought [297]. However, on a slightly longer time scale, from 1982 to 2009, this same area in northern Finland shows increasing vegetation productivity [298], suggesting that any drought-induced declines in vegetation productivity until 2002 was quickly compensated for during the period 2002-2009.

Northern wetlands are sensitive to drought. During the 2018 summer heatwave hitting north-western Europe, photosynthetic activity of wetlands in Sweden and Finland (including study sites near Swedish and Finnish hubs) was reduced due to a widespread water table drawdown [299]. It also led to reduced methane emission, turning three out of the five monitoring sites from CO_2 sinks to sources. However, it was not stated whether the mire vegetation at these sites showed signs of physical damage to tissues.

Heatwaves in the Arctic tundra are becoming more frequent. An anomalously warm July on Svalbard had purely stimulatory impacts on biomass production of a mesic tundra ecosystem characterized by herbs and graminoids [300]. A reason for such positive response to a heatwave is that this mesic tundra type has constant water access through water seeping in from higher altitudes and through thawing permafrost. Thus, a heatwave for such tundra types is to lesser extent associated with drought-related effects. On the other hand, numerous other experimental and observational studies manifest that summer drought indeed have negative impacts on both plants and soil organisms in arctic tundra [301]. Seedlings are particularly vulnerable to summer drought, and windswept ridges provide the most severe environments in terms of temperature and drought stress [302]. With the increasing climate change-induced thawing of snowbeds, plants adapted to such environments become more exposed to drought, and this is the reason why numerous snowbed species, and the entire snowbed ecosystem, are in decline and red-listed; see section 4.1.2 for more information on snowbeds.

Extreme rainfall events during the warm season will occur more frequently, and there is already an increasing trend over northern regions. Such events cause damage both to the physical, biotic and human environment. They often trigger flash floods leading to high sediment transfers, uprooting or erosion of alluvial vegetation, increased mortality of fish and other aquatic

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[297] Angert et al. 2005
[298] Piao et al. 2020
[299] Rinne et al. 2020
[300] van der Wal & Stien 2014
[301] Bell & Bliss 1980, Gauslaa & Odasz 1990, Hertzberg & Leinaas 1998.
[302] Billings & Mooney 1968, Bell & Bliss 1978, 1980

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organisms, and damage to infrastructure and agricultural lands [303]. In steep terrain, landslides and rock avalanches are common after heavy rainfall. In Norway, which is a country with much steep terrain, a landslide forecasting-and-warning service was launched in 2013 with the main goal of reducing economic and human losses caused by landslides [304].

Vegetation is sensitive to heavy rainfall. Such events can negatively affect commercial plants and plants in their natural environment. For example, during heavy rainfall flowers can be physically damaged, nectar can be diluted, pollen can be degraded, and flowering length can be severely reduced. At the same time, pollinators become less effective through mechanical and energetic constraints, along with disruption of foraging patterns and disruption to sensory signals [305]. Heavy rainfall during fruit maturing has similar negative effects on development and quality and increases susceptibility of fleshy fruits to mould infections [306].

Windstorms have potentially major negative impacts on vegetation. Wind-felling of trees often occurs and tend to affect managed even-aged spruce stands more than mixed stands of deciduous trees, and, as reviewed by Potterf et al. [307], climate change will likely further amplify wind damage to trees due to the increasing frequency of strong winds, increasing growing stock, and shortening of the frozen soil period resulting in lowered tree ground anchorage during the windiest time of the year.

Overall, extreme weather events during the growing season will increase in frequency within the ArcticHubs study region − with potential major consequences for nature and nature-based economies; see further treatment in sections 4.3 and 5.2.

4.3 Future terrestrial ecosystem changes due to climate change (2023-2100)

Despite increasing stress to vegetation due to winter climate change and more extreme events in summer, the boreal and arctic biomes are by and large becoming greener. The ongoing greening trend is attributed to increasing growth rates of in situ vegetation and northward and upward expansion of thermophilic plants, see Section 4.1.1.

Poleward expansion of species is projected at an accelerated rate. Altered vegetation contribute to warming through impacts on surface albedo and the sensible heat flux [308]. Increasing leaf

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[303] Beylich & Sandberg 2005, Bjerke et al. 2014, Ledger & Milner 2015, Nilsson et al. 2015, Marshall et al. 2020
[304] Krogli et al. 2018
[305] Jentsch et al. 2009, Lawson & Rands 2019
[306] Akan & Fortes 2015, Bui et al. 2021
[307] Potterf et al. 2022
[308] Foley et al. 1994, Levis et al. 2000, Serreze & Barry 2011

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area at northern latitudes has a self-renewing effect; with continued warming, positive feedbacks between climate and vegetation (increasing biomass and earlier leaf-out) are amplifying warming, which is a process that will accelerate during the 21st century [309].

As the winter season is warming faster than the summer season, the difference between summer and winter temperatures is diminishing over time. Analysis of simulations from 17 state-of-the-art climate models indicates that an additional seasonality diminishment equivalent to a 20° equatorward shift could occur this century [310].

The poleward expansion of species from gradual warming and the increasing frequency of extreme weather events will have massive impact on the distribution and relative abundance of ecosystems and plant functional types at high northern latitudes, both on land and in sea. However, there are uncertainties in how these changes will affect future ecosystem change, given that it is hard to predict the relative importance of trend changes in temperature and precipitation vs. the increasing frequency of extreme weather events causing direct or indirect damage to vegetation. Wind-felling of trees and anoxia damage to tundra vegetation from rain-on-snow events are examples of direct damage, while vegetation damage from landslides or flash floods caused by heavy rainstorms are examples of indirect damage. Moreover, increasing frequencies of biotic events (e.g., forest fires, tundra fires, thermokarst formation, pest outbreaks) further complicate the projections.

Models relying on trend-based climate change project a northward and upward expansion of major terrestrial ecosystem types, for example that temperate mixed broad-leaved forest will expand its range in southern Scandinavia, that boreal deciduous and conifer forests will move both northwards and upwards in the Nordic region, and that alpine tundra will decline drastically, with concomitant changes to net primary productivity [311]. These trends are strongly reflected in the Red Lists of species and habitats; see treatment in Section 4.1.

See sections 4.1.3 and 5.3 for ongoing and future changes to marine ecosystems.

Incorporating events into the modelling results in projections that deviate from trend-based model projections [312]. Under an RCP8.5 scenario, approximately 30 % of global land areas will experience changes in dominant vegetation type, both with and without extreme weather events employed in the modelling [313]. However, projected changes with or without extreme weather

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[309] Swann et al. 2010, Serreze & Barry 2011, Cho et al. 2018, Xu et al. 2020
[310] Xu et al. 2013
[311] Hickler et al. 2012, Ito et al. 2020
[312] Forkel et al. 2019, Beigaitė et al. 2022
[313] Beigaitė et al. 2022

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events differ regionally. For northern Europe and Greenland, a slightly larger proportion of land area will change when climatic extremes are incorporated into the model than in the same model without climatic extremes (Figure 4.8). This is particularly the case for southern regions of Finland, Sweden and Norway, and for the northernmost, coastal region of Troms and Finnmark in northern Norway. Iceland, on the other hand, will change more without extremes than with extremes. There are very little differences between the two models for the arctic regions of Greenland and Svalbard. In practice, the dominant vegetation type of all ice-free land areas of Greenland and Svalbard will change, irrespective of whether extremes are included in the model or not. However, extremes may affect the direction of change, i.e., which new vegetation type will establish. The model also shows that a large section of the Greenland ice sheet will become ice-free and vegetated (orange dots in both panels of Figure 4.8).

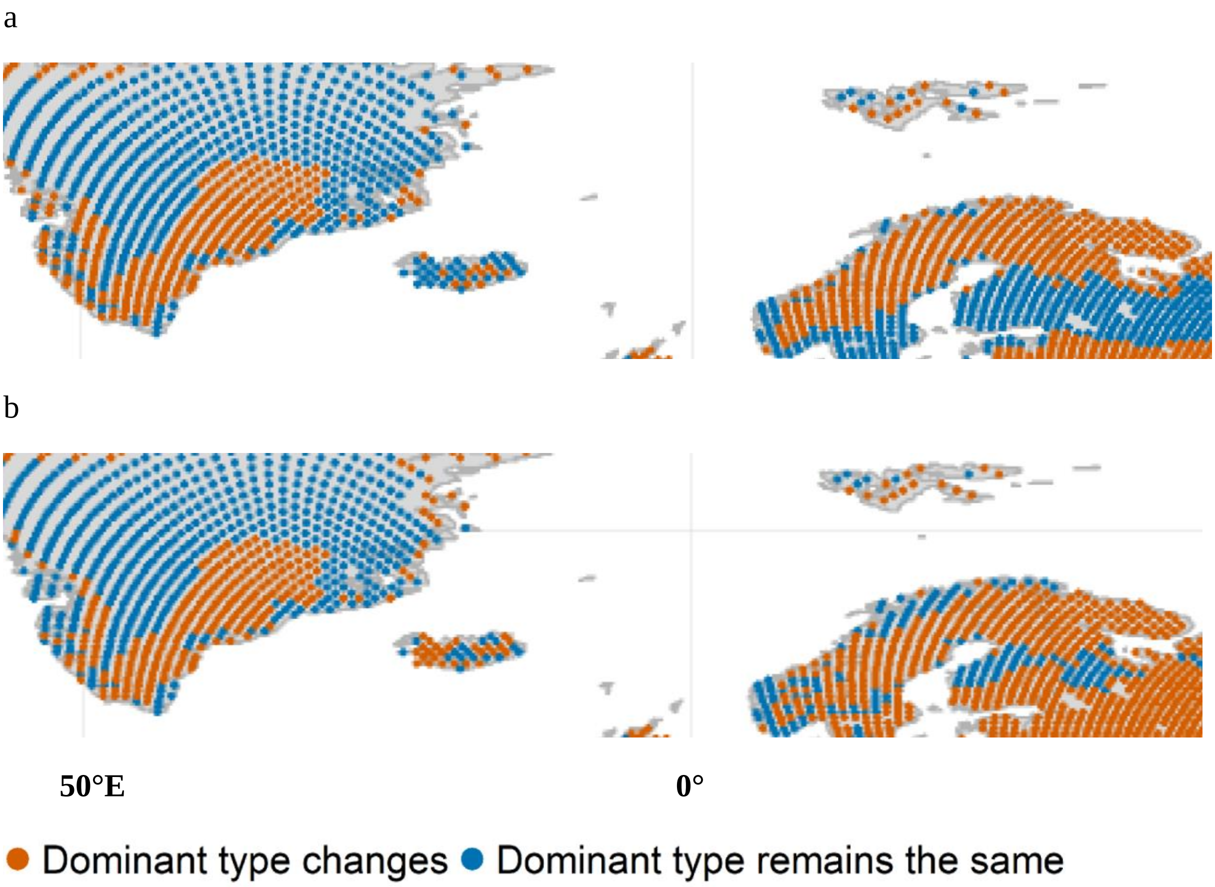

Figure 4.8. Change in dominant vegetation type by 2060-2080 under the RCP 8.5 scenario for northern Europe and large parts of Greenland. (a) Predictions by decision tree with extremes. (b) Predictions by decision tree without extremes. Reproduced from Figure 6 in Beigaitė et al.[314]. Disclaimer: Before this figure is reproduced in any public report, permission must be applied.

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[314] Beigaitė et al. 2022

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5 Impacts of climate change on the target activities of ArcticHubs – recent and future

This chapter elaborates on the way climate change is affecting, and will affect, the target activities of ArcticHubs, i.e., indigenous activities, tourism, mining, forestry, and mariculture (fish framing, etc.). This is primarily a review of already published material. The impacts of climate change on these activities are a focal topic of several other reports to be produced in this project. Thus, in this report, a broad overview is provided, which can act as a jumping-off point for more rigorous evaluations, including data from interviews and DPSIR analyses, in upcoming ArcticHubs reports.

For tourism and indigenous issues, the treatment is separated into the cold season (section 5.1) and the warm season (section 5.2), as impacts differ substantially between seasons. Fish farming (section 5.3), forestry (section 5.4) and mining (section 5.5) are not split according to season.

5.1 Cryosphere (snow, ice and permafrost) and winter climate change

5.1.1 Indigenous and other local people's activities

5.1.1.1 Reindeer husbandry

Climate and land use changes have led to numerous challenges for reindeer herders whose livelihoods rely on an accessible and healthy ecosystem with predictable weather patterns. Reindeer herders have reported rather unanimously more variable weather, higher temperatures, more frequent winter rainfalls and increased windiness compared to earlier decades [315]. In addition, increased snow depth, but later snow cover formation, and earlier snow melt have been reported [316]. The herders' observations coincide rather well with meteorological data [317]; see also Chapter 4.

Reindeer herders in Sweden, Finland, Norway, and Russia report a series of different negative consequences as a result of changing climatic conditions during all grazing seasons. The timing of snow melting during spring seasons affects the timing of the long spring migrations from coastal and inland forest to the foothill mountains. An earlier-than-normal snow melt in winter

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[315] Turunen et al. 2016, Horskotte et al., 2017, Rasmus et al. 2020, 2022

[316] Turunen et al., 2016, Näkkäläjärvi et al. 2020

[317] Löf et al 2012; Markkula et al. 2019, Rasmus et al. 2020, Skarin et al. 2021

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grazing areas forces an early start of migrations towards calving areas. However, early arrival to calving areas is sometimes hampered by too much snow at the point of arrival. Furthermore, long-lasting, deep snow during the calving season has become a concern during later years. Furthermore, increasing numbers of predators has limited the possibilities to use low-elevation, forested foothill areas that have shallower snow cover, and would have been suitable for calving if it was not for the predator risk. During the actual spring migrations, warming spring weather have negatively affected ice conditions on lakes and rivers. Here, hydroelectric developments along most river systems in Sweden has further deteriorated ice conditions and forced displacement of migrations routes into adjacent often intensely managed forest lands.

High summer temperatures have had negative impacts on reindeer health as well as grazing conditions. Late-season snow patches in the mountains have traditionally been important refuges for reindeer during warm days, but the remaining snow patches have become fewer and smaller resulting in negative effects on reindeer health. In particular, warm summer temperatures have become a serious concern in forest reindeer herding communities such as Malå and Gällivare. Herders in these communities also report on increases as well as changes in timing of impacts from insects. Insect harassment in combination with warm weather is believed to have negative consequences and reindeer health and wellbeing. From Malå, we have documented major shifts in reindeer space use as reindeer leave their traditional summer lands and spontaneously move to fall and winter areas already in July. Several factors are believed to contribute to this, including phenological timing, shifts in insect distribution, as well as an earlier onset of the mushroom season [318]. Here, the increasing impacts of other land use practices also play a major role, as exemplified through a series of new wind power developments in Malå, increasing clearfelling (see treatment in 4.1.1), as well as expansion of mining areas in Gällivare. Increased land use pressure reduces the resilience of husbandry systems and worsen the negative impacts of climate change.

Warm autumns can cause herds to disperse over a wide area (‘‘break loose”) in search of forage, which complicate the gathering of reindeer and the subsequent migration to the round-up sites [319]. Temperature can also affect rutting; during warm autumns rutting tend to start later or be unsynchronized [320]. The combination of disturbed rutting, the absence or sporadic distribution of snow, the occurrence of mould on pastures, the formation of ground-ice, in combination with the abovementioned herd dispersal, result in very challenging autumn conditions for herders

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[318] Skarin et al. 2021
[319] Turunen et al. 2016
[320] Rasmus et al. 2020

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[321]. These autumn challenges are even more accentuated in areas where lichen biomass has declined to very low levels following enduring, extensive utilization.

When round-up and slaughtering are delayed due to warm autumn weather, herders end up with less meat for sale, since calves rapidly lose weight with the onset of frosts and snow cover formation, particularly if the herding is based exclusively on natural pastures. Herders respond to these conditions by more active gathering and moving, and increased monitoring of herds to prevent traffic accidents or losses to carnivores [322].

During autumns with unseasonally late formation of a permanent snow cover, reindeer need to be gathered and moved to the round-up sites using all-terrain vehicles or helicopters instead of snowmobiles. Belated and incomplete ice formation on waterbodies and late freezing of bogs make gathering even more challenging, as these conditions hinder migration between seasonal pastures. The reduced bearing capacity of ice poses risk to both reindeer and herders; late ice formation may facilitate herding, because, in some reindeer herding communities, open water bodies can provide effective barriers; while in other reindeer herding communities, reindeer tend to cross rivers or lakes with thin ice, but often fall into the water and must try swim to the shore, though often with fatal consequences [323]. There are also several known incidents of herders drowning from falling through thin ice [324]. In Sweden, trucks may be necessary in some herding communities to transport reindeer between different seasonal pastures because of lost migration routes or unsafe ice conditions [325].

Winters with long snow-free periods or a thin snow cover can provide better opportunities for grazing, and mild winter weather can help reindeer maintain good body condition [326]. In the case of early snow melt, the availability of fresh, green, soft forage increases, which is favourable for lactating reindeer and their new-born calves. Late snow melt can greatly decrease the availability of forage for pregnant or lactating reindeer, and be fatal for new-born calves, which can perish in deep and soft snow or be easily caught by predators [327].

Warm winters have more frequent and longer-lasting thaw events. Increasing frequency of freeze-thaw cycles or rain-on-snow events cause formation of very dense snow or ice layers on

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[321] Rasmus et al. 2022
[322] Turunen et al 2016, Rasmus et al 2020, 2022
[323] Löf et al., 2012, Turunen et al., 2016, Näkkäläjärvi et al. 2020, Nystad & Gaup 2021
[324] Ahlm et al. 2010
[325] Löf et al. 2012, Rasmus et al. 2022
[326] Helle & Kojola 2008
[327] Vuojala-Magga et al. 2011, Turunen et al. 2016

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the ground or within the snowpack [328]. Formation of ground ice can severely deteriorate the grazing conditions of reindeer ("locked pastures"). Decreased accessibility to ground vegetation due to ice, icy snow and/deep snow may lead to increased reindeer mortality and reduced calving success. During the winter 2019/20, the northern parts of Finland, Sweden and Norway experienced an exceptional winter. There was a heavy snowfall starting in autumn, which increased throughout the winter and led to formation of landscape-scale icy crusts. Reindeer were not able to dig through the snow and ice for forage, resulting in high reliance on supplemental feeding. Herders in Sweden and Finland had to start feeding much earlier than during normal winters, while herders in Norway, who normally do not rely on supplemental feeding [329], had to purchase tons of forage that were flown into winter herding areas. The severe conditions this winter resulted in reindeer exhibiting poor physical condition, an increase in reindeer mortality, and greatly reduced slaughtering numbers [330].

The most recent winter (2021/22) was even just as challenging as the 2019/20-winter. The 2021/22 winter is not yet covered in scientific literature, but news reports which include interviews with herders, draw a picture of poor grazing conditions due to temperature fluctuations around the freezing point combined with much snowfall early in the season [331]; see also Section 3.1.3. The high snowfall on the Norwegian side led to increased avalanche risk; and in a valley in Troms, around 70 reindeer were killed in an avalanche [332].

In Finland regular winter feeding either on pasture or in enclosures became part of the herding system in the southern and central parts of the reindeer management area in the late 1980s and mid-1990s, mainly as a result of the detrimental impact of forestry on lichen resources [333]. Changing winter conditions together with competing land use have enhanced the need for supplementary feeding. However, many herders in Norway and Sweden report that feeding increases vulnerability and is not a preferred adaptation in the long run [334]. The heavy reliance on supplemental feeding requires purchase, or own agricultural production, of forage [335], greatly increasing economic costs. Long transport routes, which often is the case, severely increases the costs of purchasing supplemental forage. Supplemental feeding also tends to tame the reindeer, which makes them more difficult to gather and move – and increase the risks of

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[328] Bulygina et al. 2010, Vikhamar-Schuler et al. 2013, 2016, Bokhorst et al. 2016, Riseth et al. 2016, Rasmus et al. 2018, 2022, Peeters et al. 2019, Nilsen et al 2020
[329] Paulsen 2021
[330] Kumpula et al. 2020
[331] Oskal et al. 2022
[332] Wilhelms et al. 2022, Solvang 2022
[333] Turunen & Vuojala-Magga 2014, Turunen et al. 2020, Åhman et al 2022
[334] Horskotte et al. 2020, Rasmus et al. 2022
[335] Turunen & Vuojala-Magga 2014

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predation and outbreaks of infectious diseases [336]. There is also a fear that supplementary feeding may profoundly change herding cultural traditions, as reindeer lose their wild characteristics and their ability to graze and survive on their own in nature [337].

The impacts of variation in environmental and climatic conditions on the abundance of reindeer cows that produce calves have, until recently, not been included in demographic models. The proportion of reindeer cows that bring calves has previously been based on pregnancy rates and the assumption that the early natural loss of calves from calving to earmarking/counting of calves has been estimated to 6% [338]. Using environmental data such as snow conditions during winter, the timing of spring and the amount of available forage the following summer Tveraa et al. [339] have recently developed an improved model for estimation of early and natural loss of reindeer calves. This new model explains between 37 and 90 % of the variation in the increment of calves in Norwegian reindeer populations. This provides new knowledge of how reindeer husbandry is affected by year-to-year variation in climatic, grazing and environmental conditions, and how large the proportion of surviving calves would be under different scenarios.

In Supporting information, chapter 7.3, we provide a detailed assessment of year-to year variation in late-winter snow season and snowmelt timing for one hub (Kvalsund-Kautokeino), emphasizing the impacts of snow season on forage availability in spring.

5.1.1.2 Fishing and hunting

Extremely warm winter events affect local arctic communities; the decreased ice coverage challenge traditional food systems and increase food-related stress [340]. Coastal fishing and hunting traditions of local communities in Greenland are affected by climate change. Sea-ice is retreating, which hampers traditional hunting and hinders the provision of basic food for humans and dogs [341]. Reduced utility of sled dogs has led to a rapid decline in total number of dogs in Greenland [342].

For the traditional late winter (March-April) fjord fishing of halibut and hunting of ringed seal, reduced fjord ice can in fact be advantageous for two reasons. First, ice-rich fjords limit

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[336] Tryland et al. 2019, Paulsen 2021
[337] Risvoll & Hovelsrud 2016, Turunen et al 2016, Rasmus et al 2020, 2022, Ocobock et al. 2022
[338] Tveraa et al. 2016
[339] Tveraa et al. 2022
[340] Statham et al. 2015
[341] Hastrup et al. 2018
[342] Sonne et al. 2018

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visibility reducing the ability to navigate, hunt and fish. Second, boats are increasingly used for fishing and seal hunting, which provides increased mobility than the traditionally used dogsled [343]. Still there are numerous negative aspects of climate change for this fjord system: halibut leaves sections of the fjord affected by increasing frequency of muddy freshwater released from an ice-dammed lake; locals without boats, relying on dogsled to reach the fjord, come in fewer numbers because of limited access; the marine ecosystem is under change which brings fear of reduced halibut and ringed seal in the future.

Climate-induced and environment-induced changes to marine ecosystems have forced peoples of southwest Greenland to rapidly adjust their resource harvesting – from seal hunting to cod fishing, then from cod fishing to shrimp [344]. While harvesting of marine resources in south-west Greenland has become challenging, shorter winter seasons may facilitate agricultural intensification and expansion in the area [345].

Winter hunting of musk oxen has been lucrative due to high prices on winter skins. However, hunting (in all seasons) contributed to the muskox decline of the early 1900s. Not all populations of musk oxen are in good condition, and climate change will worsen the conditions for this high-Arctic animal. Traditional indigenous harvesting of products from musk oxen is therefore in decline [346]. It is not clear how climate change will affect future caribou hunting in the Nuup Kangerlua area. Currently, the western Greenland population is considered as being of Least Concern (LC), i.e., it is not threatened [347]. If the population remains stable, harvesting may continue at current rates, at least at short time horizons. However, Inuit communities on the Canadian side of the Labrador Sea have suffered from recent caribou population declines, which are partly related to climate [348], indicating that similar climate-induced changes in caribou herd size may also soon take place in western Greenland.

5.1.2 Tourism

Tourism is in this report treated in two sections: cryosphere and winter (this section) and summer (section 5.2.2). The introductory paragraphs to this section 5.1.2 are also relevant for summer tourism.

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[343] Schiøtt et al. 2022
[344] Hamilton et al. 2020
[345] Caviezelet al. 2017
[346] Jørgensen 2019, Cuyler et al. 2020, Andersen 2022
[347] Boertmann & Bay 2018
[348] Borish et al. 2021

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Arctic tourism is mainly based on natural experiences and local – and often indigenous – cultures. Consequently, both ecological and social sustainability are important for the future of Arctic tourism. The nine tourism hubs differ in activities and marketing strategies due to different aspects such as location, accessibility, cultural history, and local economies. Overall, there is an ongoing enhanced interest in Arctic destinations resulting in more anthropogenic pressure on the fragile natural and cultural landscapes characterising the area. At the same time, as mentioned in previous chapters, the Arctic is experiencing current climate change and intensified extreme events that affects local ecosystems and communities. Even though there are several inequalities, all hubs have experienced increasing traffic during the past years and will have to face coming changes in the tourism industry due to climate change.

"Last-chance tourism" is a term that has emerged in the last decade [349], generated from climate change. It is a concept that involves experiencing climate change by seeing melting glaciers, disappearing landscapes or seascapes, and disappearing nature and communities. With increasing climate change the interest in last-chance tourism is likely to grow in the years to come.

With increased tourism, seasonal fluctuations, which have long characterized Arctic tourism, have during the past two decades decreased to some extent. The length of the tourist season has strengthened the foundation of tourism as an important industry in the Arctic. This applies to all the nine tourism hubs. Nature-based tourism in the Arctic mainly involves activities such as hiking, running, biking, climbing, horse-back riding, see-angling, bird watching, whale watching, cruise and expedition tourism, sightseeing, and all kinds of motorized nature activities.

Arctic tourism in winter season involves activities such as winter cruise tourism, general winter activities, hiking, skiing, dog sledding, scooter tours, visiting ice caves, and watching northern lights. For many long-distance travellers, their holiday to an Arctic destination is also their first encounter with snow. Thus, very basic activities such as holding snow in their hands, walking on snow, and making a snowball, are for these tourists an exceptional experience. Other popular all-season activities also include visiting cultural heritage sites, enjoying local food and beverages, and specifically in Svalbard visiting mines.

In response to climate change, the local tourism in the Arctic will face a growing number of changes and challenges that it needs to adapt to soon. Lack of snow in wintertime will have

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[349] Lemelin et al. 2010, Hall et al. 2020

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negative consequences for traditional winter tourism [350], retreating glaciers will impact the stability of ice caves, and declining sea ice leads to a cascade of consequences for marine wildlife, indirectly causing increased human disturbance, more chemical pollution and noise that will alter the structure and function of entire ecosystems [351]. In terrestrial ecosystems we see consequences from ongoing cryospheric and hydrological changes, such as thawing of permafrost and retreat of glaciers causing increased risk for landslides and affecting accessibility to popular destinations.

Cruise tourism is one of the fastest growing tourism industries in the Arctic. Due to shrinking and thinner sea ice, the Arctic is becoming more accessible for longer cruise seasons, apparent in hubs such as Longyearbyen and Nuup Kangerlua [352], which in turn is likely to lead to more cruise traffic, and subsequently increased greenhouse gas emissions, and potential negative aspects on marine wildlife. The number of cruise ship visitors in the High Arctic increased with 57 % from 2008 to 2017. In Iceland there was an increase of 66 % from 2015 to 2017, and ports in northern Norway experienced an increase of 33 % from 2014 to 2019[353]. In response to increased accessibility and more attractions in these areas, the tourist footprint has increased with 600 % in winter season over the past two decades [354].

Lack of snow is a big issue in inland tourism in northern Scandinavia where winter and especially Christmas time is the high season. In addition to downhill and cross-country skiing, all other activities such as husky or snow mobile safaris require snow. Downhill skiing can be handled by production of artificial snow, but for longer routes it is difficult to produce sufficient amounts. In the Alps, the survival of ski resorts implies an increase in snowmaking requirements, and their associated costs and environmental consequences [355]. While the costs and concerns of the lack of snow have been biggest in the Alps, the lack of snow and the need for artificially produced snow or snow stored over summer, especially for the early winter tourism, has already become a problem also for Arctic ski destinations [356].

For numerous winter tourists, especially from lower latitudes, watching northern lights is a primary reason for their travels to the far north [357]. The Northern lights are a flickering and unpredictable phenomenon which poses challenges for providers of Northern Lights tours as

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[350] Jansson et al. 2015, Rice et al. 2021
[351] Arctic Monitoring and Assessment Programme 2017
[352] Treated in previous reports of the ArcticHubs project
[353] AMAP 2021
[354] Runge et al. 2020
[355] Demiroglu et al. 2020
[356] Kietäväinen & Tuulentie 2013
[357] Heimtun et al. 2015

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well as for tourists who take part in numerous Northern Lights trips, at times without ever actually catching glimpse of the lights [358]. Northern light activity is particularly strong in a belt around ca. 65-65 °N. Hence, northern parts of Finland, Norway and Sweden are attractive for northern lights tourism. Climate change may affect the future of the northern lights tourism industry, partly due to the projected increase in cloudiness and decline in snow cover. Clouds disrupt the visibility; hence, tourists will avoid areas with a reputation of frequent cloud cover. Watching northern lights in combination with snow is particularly attractive, especially in mountainous coastal landscapes where snow-capped mountains provide a beautiful frame for northern lights-lit skies. This is the typical advertised view of northern lights to attract tourists to coastal northern Norway. If mountains are free of snow, they appear dark and may dampen the tourists' astonishment of the skyline. Northern lights tourism in Sweden and Finland often take place in early winter season before snow settles, and tourists often view the northern lights through a conifer canopy, or from open areas without any landscape features framing the skyline. The inland areas of Sweden and Finland and Kautokeino in Norway are, and will be, less cloudy than coastal areas of northern Norway. Overall, the Finnish and Swedish northern lights tourism may therefore be less affected by climate change than the coastal Norwegian northern lights tourism.

There are concerns about uncontrolled and seasonal mass tourism that will continue to grow, which does not necessarily benefit local communities and might harm the vulnerable Arctic natural ecosystems. This clearly shows the need for more adaptation strategies and management plans across national borders to reduce risk of negative impacts from existing and future consequences of climatic, social and economic change on already strained environments.

On the other hand, The Arctic as a niche destination is a fragile concept both regarding changing ecosystems and a potential growth of tourism towards over-tourism in the high seasons [359]. As climate change intensifies, and negative impacts become more prominent in international narratives, more arctic tourists might begin to avoid air travels or specific destinations to cause less harm to the global climate, and to the local environment, communities and ecosystems [360].

Changes in precipitation and extreme weather events might furthermore affect transport and infrastructure which in turn might restrict accessibility to arctic destinations. A potential result of less travels might be more domestic and less international tourism.

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[358] Jóhannesson & Lund 2017

[359] Ólafsdóttir et al. 2020

[360] Alcock et al. 2017, Gössling & Dolnicar 2022

The consequences of Arctic climate change require planning and adaptation [361]. However, Salim et al. [362] point out that most of the adaptation strategies implemented by tourism operators due to climate change in the Alps have been reactive, mainly consisting in the installation of safety equipment, the renovation of access and viewpoints or construction of new infrastructures to allow tourist activities to continue despite the consequences of climate change. There is likewise a need to consider other transformative strategies, such as the adoption of new activities.

5.2 Growing-season climate change

5.2.1 Indigenous and other local people's activities

5.2.1.1 Reindeer husbandry

Reindeer herders' reports of increased number of warm days, increased precipitation and heavy rains in summer coincide well with meteorological observations [363]. Heat increases thermal stress in reindeer, which are adopted to cool summer climate [364]. Calves suffer disproportionately from long periods of warm weather and the concomitant insect harassment. Insect harassment affects weight and reproduction and increases mortality because stressed reindeer spend less time grazing, and their energy expenditure increases [365]. They also suffer from heavy rains, which are strongly associated with warm weather periods. Heat and insect harassment draw reindeer into large herds, which facilitates gathering and moving of animals for calf-marking during June and July. Handling of reindeer during heatwaves causes additional stress. Therefore, the calves are often marked at night. Marking of calves can also be postponed, and during very warm summers calves are left unmarked until the autumn round-ups [366].

Longer growing seasons and increasing effective temperature sums result in densification and expansion of forests northwards and upwards [367]. The most profound negative impacts will be on palsa mire and fell ecosystems, snowbeds and snow patches (see Section 4.1.2), which are valuable grazing areas for reindeer during long warm periods and when harassment from insects

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[361] Kaján & Saarinen 2013
[362] Salim et al. 2021
[363] Näkkäläjärvi et al. 2020, Rasmus et al. 2020, 2022
[364] Soppela et al. 1986
[365] Weladji et al. 2003
[366] Turunen et al. 2016, Rasmus et al. 2020, 2022
[367] Pääkkölä et al. 2018, Markkula et al. 2019

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are intense [368]. These climatic changes with associated behavioral changes in reindeer, have consequences for herding practices: for example, calf marking sites may need to be relocated [369].

Warming-induced outbreaks of geometrid moths is expected to increase both in space (area) and time (frequency); see Chapter 4. Such outbreaks will reduce biodiversity and the overall nutritional value of forage available to reindeer. The volume of lichens, a preferred reindeer forage, is expected to decline with increasing warming, partly because of improved growing conditions for vascular plants that may outcompete lichens through higher growth rates or invade more rapidly into vegetation-free areas previously covered by lichens, but where lichens have been excessively removed during periods of high reindeer densities [370]. In addition, forest fire risk is increasing – both due to increasing frequency of summer drought periods and lightning, and this will add to the already heavy pressure to which reindeer husbandry is exposed.

Warming-induced changes in the distribution and epidemiology of infectious diseases creates new risks for both reindeer and reindeer herders. For example, warmer and wetter conditions and increase in shrub and forest vegetation can increase tick distribution and abundance [371]; see also chapter 4. Parasitic epidemics and new invasive alien species are part of this cocktail that will put increasing pressure on reindeer husbandry [372]. When reindeer are gathered in enclosures for calf marking, there is a risk of disease outbreaks and parasite transmission, particularly in wet, muddy conditions [373].

In Supporting information 3, we provide a detailed assessment of year-to year variation in spring and summer conditions for one hub (Kvalsund-Kautokeino), highlighting the large variability in spring green-up and summer greenness. The large variation between years has always posed challenges for reindeer herders in their planning of migrations, and increasing climatic change will further reduce predictability.

5.2.1.2 Fishing and hunting

In the Faroes, traditional harvesting of natural resources (fishing, sheep-rearing, whaling, harvesting of seabirds and eggs, etc.) continues to contribute significantly to the Faroese diet

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[368] Pääkkölä et al. 2018
[369] Horskotte et al. 2017, Rasmus et al. 2022
[370] Sedia & Ehrenfeld 2003, Cornelissen et al. 2004, Tømmervik et al. 2004, 2009, 2012, Turunen et al. 2009
[371] Hvidsten al. 2020
[372] Härkönen et al. 2010, Laaksonen et al. 2010
[373] Rasmus et al 2022

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[374]. The availability of these resources for local people crucially depends upon a combination of environmental/climatic and socio-political conditions. In recent years, seabirds and fish, in particular, have declined in the coastal areas, and although the exact causes are not completely understood, climate variation and change are most likely a defining cause; see section 4.1 on seabird collapse.

In southwest Greenland, melting glaciers stimulate large summer phytoplankton blooms, which may affect fishery resources in the future, if such bloom become even more frequent [375].

5.2.2 Tourism

This section supplements Section 5.1.2 where general tourism issues were discussed in concert with cryosphere and winter tourism.

Even though the winter might be the high season for tourism in most of the hubs, summer tourism is also important in these areas. First, cruise tourism is a main attraction for the hubs near the coast, including sightseeing and guiding from a growing number of landing sites. Especially in Nuup Kangerlua and Svalbard, the cruise tourists alternate between cultural and nature-based activities, e.g., visiting museums and cultural heritage sites as well as watching glaciers, marine mammals or birds. In Svalbard and northernmost Norway, midnight activities are particularly attractive since the midnight sun is exotic and a new experience for many international travellers [376]. Other popular summer activities involve hiking, biking, water activities, and fishing. Tourists also come to see pristine picturesque landscapes. In Inari and Kittilä, visiting the national parks is a popular activity, and on Suðuroy tourists come to visit small settlements and villages. In the hubs Nuup Kangerlua and Svalbard, watching glaciers is an important activity.

Changes in summer climate involves higher temperatures in the Arctic. Especially in the summer season, more summer outdoor activities and potential mass-tourism is expected in all hubs as the Arctic becomes warmer and more appealing as nature tourism destinations helped by the Right of Public Access, as compared to destinations at lower latitudes where summer weather may become too warm to be pleasant [377], as was the case in 2022 during the extreme

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[374] Bogadóttir 2020
[375] Arrigo et al. 2017
[376] Favero 2000, Prebensen 2007, Rowsell et al. 2017
[377] Jansson et al. 2015, Arctic Monitoring and Assessment Programme 2017

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summer heat and drought of central and southern Europe. Travelling to avoid heat is in some studies termed as heat-escape tourism [378].

‘Overtourism’ is a relatively recent concept commonly associated with cities such as Barcelona and Rio de Janeiro; though not a precise term, all definitions of overtourism incorporate negative experiences, which lead to host communities becoming less amenable to, or able to cope with, tourism [379]. Overtourism is already a challenge for certain northern communities. In Svalbard, indicators of overtourism include lacking facilities when cruise ships arrive, increasing sewage and organic waste discharged untreated into the sea, increasing rate of tourism-related fatalities, erosion of vulnerable arctic tundra from large groups of people walking in nature (often enroute to cultural heritage sites), and highly limited ability for rescue operations if something should happen to a cruise ship or any other large group of tourists [380]. These challenges are not new for Svalbard [381], while a climate change-induced rise in arctic tourism will put even more pressure on small, northern communities.

As reindeer husbandry becomes more unstable and the business/economies are strained because of less favourable conditions due to climatic change, the reindeer herders will have to rely even more than today on income from tourism. This includes trading of handicrafts and meat and offering guided Sami activities to tourists [382]. In a rapidly changing world with resulting changes in global food security, small-scale family-sized farms might profit in tourism business as there is a growing trend for small-scale local food production [383].

5.3 Fish farming

Mariculture hosts a unique potential for increasing seafood production and at the same time reducing greenhouse gas emissions from food systems [384]. Climate change may both constrain and enhance blue growth in the selected fish farming hubs. A rise in seawater temperature may constrain cultivation of cold-water species in southernly areas but may open for cultivation of new species that thrive better at warmer temperatures. In turn, cultivation of cold-water species will be more profitable in the North due to longer growing seasons [385]. In the following we will

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[378] Kong et al. 2019, Steiger et al. 2022
[379] Saville 2022
[380] Thuestad et al. 2015, Holmgaard et al. 2019, Hovelsrud et al. 2020, Kaltenborn et al. 2020, Saville 2022
[381] Kaltenborn & Emmelin 1993
[382] Müller & Huuva 2009, Olsen et al. 2016, Ayaydın & Akgönül 2020, Saari et al. 2020
[383] Rikkonen et al. 2013
[384] Jones et al. 2022
[385] Thyholdt 2014

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mainly focus on the impacts of climate change on the economically most important species farmed in the three different fish farming hubs, the Atlantic salmon (*Salmo salar*). The production cycle of Atlantic salmon starts in a land-based freshwater hatchery where Atlantic salmon smolts are produced in either water-intensive flow-through systems or energy-intensive, but water-saving recirculating aquaculture systems (RAS). Thereafter, in most cases, seawater-ready smolts are transferred to sea cages for grow out [386]. Climate change will likely affect the entire salmon production cycle via abiotic and biotic factors, both directly and indirectly.

5.3.1 Direct impacts of climate change on the fish farming hubs

5.3.1.1 Abiotic factors

Temperature is a critical physical factor in aquaculture production. It determines the rate of almost all physiological processes, including development, growth, and maturation in ectothermic animals including fish [387]. The Atlantic salmon is a cold-water adapted species with an optimal growth at temperatures around 14°C, and good growth at temperatures ranging from 10 °C – 18 °C [388]. Prolonged exposure to temperatures above 18 °C causes a reduction in appetite and growth [389] and mortality increases rapidly when temperatures exceed 22.5 °C [390]. However, welfare issues have been reported already at lower temperatures. For instance, Atlantic salmon that were reared at 16 °C in freshwater showed a higher prevalence of lense opacities than the control fish reared at 10 °C [391]. High water temperatures also increase the risk for early maturation, causing economic loss due to growth stagnation and welfare issues [392]. High temperatures in sea cages are often associated with decreasing oxygen levels leading to hypoxic conditions holding a severe risk for mass mortality events; the risks of oxygen depletion are discussed separately below.

Whereas wild salmon can escape unfavourable water temperatures, farmed fish are trapped to the conditions of the farming environment. In land-based freshwater hatcheries, temperature is controlled through heating or cooling of the intake water. Tight temperature control requires

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[386] Bergheim et al. 2009
[387] Brett, 1969
[388] Handeland et al., 2008
[389] Hevroy et al. 2012
[390] Bartlett et al., 2022
[391] Sambraus et al., 2017
[392] Good & Davidson, 2016

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energy but is one main advantage of the highly controllable RAS systems [393]. In RAS systems, rearing water is warmed by heat generated from pumping the water through the system, facilitating year-round fast growth of the fish. This heat generation can however be problematic during summers and possible heat waves pushing cooling systems performance to its limits; a problem that occurs already today (personal communication with a fish farmer on Faroe Islands). If water temperatures in RAS become too high due to high air temperatures in the surroundings, it will directly affect salmon health and welfare. In addition, elevated temperatures lead to increased CO_2 levels due to the higher metabolic rates of the fish. Exposure to prolonged elevated CO_2 levels (> 12 mg/L) may cause reduced growth, osmoregulatory problems and problems associated with acid-base balance [394].

Sea cages are today the dominating production form during the grow-out phase of Atlantic salmon. Lately, alternative production strategies including land-based production throughout the entire production cycle are established around the world. Given that most of the seafood will still be produced in the sea in the fish farming hubs, climate change induced increase in water temperatures will have direct effects on Atlantic salmon growth and welfare during grow-out. Current climate models project a stronger increase in sea surface temperatures during winter than during summer along the Norwegian coast [395].

Today's average monthly seawater temperatures for the three different fish farming hubs and projected future change in sea surface temperatures are presented in Figure 5.1.

Changes in temperature of coastal waters of the different fish farming hubs by the end of the century are difficult to predict with global coarse scale models. Downscaling of the global models will provide better resolutions at a more regional scale. A recent study compared modelled sea surface temperatures for 43 fish farming sites along the Norwegian coast with on-site temperature registrations and found over- and underestimations in the range of several degrees and maximal deviations of 6 °C [396]. This study reports that, under RCP 4.5 scenario, the projected change in temperatures within 2069 will lead to less optimal conditions for salmon farming in southern Norway during summer due to a higher number of days with temperatures above 20 °C [397]. The current average winter and summer temperatures in the production area 13 (including Varangerfjord) are 4 °C and 10-11 °C, respectively [398].

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[393] Badiola et al., 2018
[394] Mota et al. 2019, Mota et al. 2020
[395] Hanssen-Bauer et al. 2015
[396] Falconer et al., 2020
[397] Falconer et al., 2020
[398] Albretsen and Asplin, 2021

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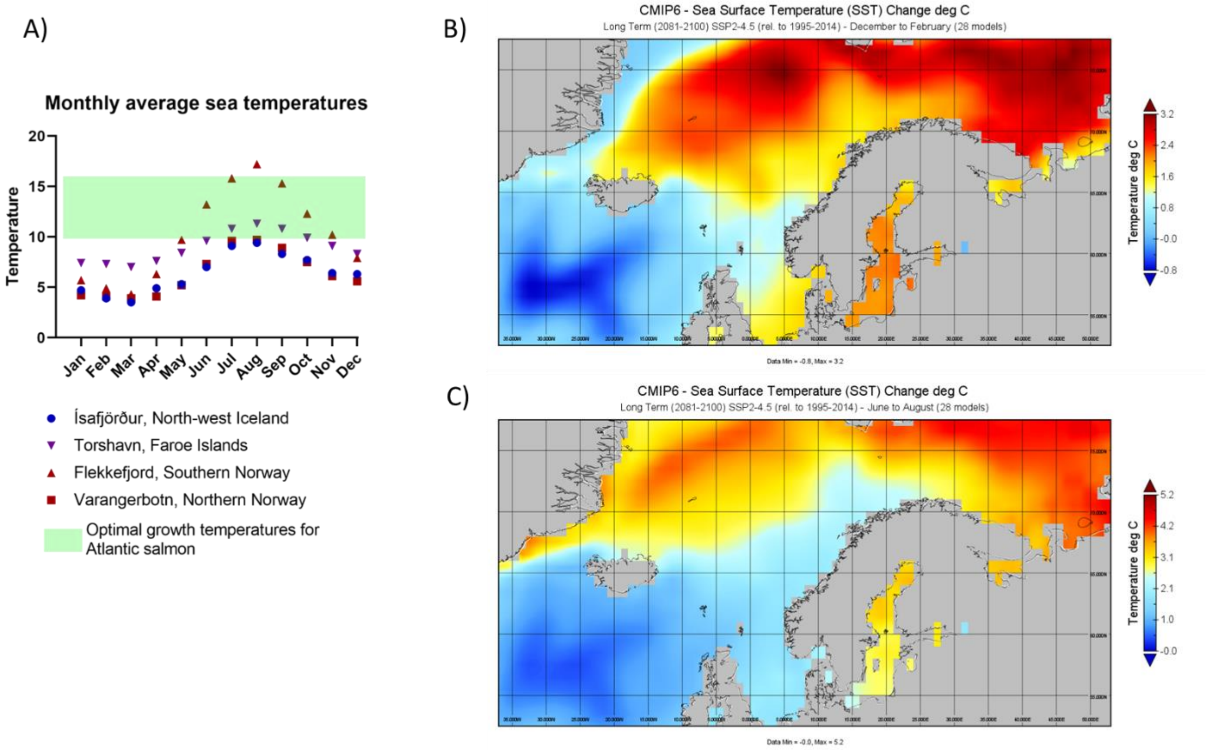

Figure 5.1. Monthly average sea temperatures for the different fish farming hubs (A) and projected increase in sea surface temperatures for winter months (December-February) (B) and summer months (June – August) (C) based on SSP2-4.5 (data retrieved from IPCC Data Distribution Center via the WGI Interactive Atlas).

Consequently, milder winters with higher temperatures could therefore lead to better growing conditions and hence positively affect salmon aquaculture in the Varanger hub. Thus, most of the growth in the Norwegian aquaculture industry is expected to occur in the Norwegian Arctic [399].

Marine heatwaves pose another threat to the fish farming industry. The frequency, duration, and intensity of marine heatwaves has increased during the past decades and a further increase has been forecasted [400]. Recent heatwaves in Newfoundland [401], and Tasmania [402] resulted in fish welfare issues and huge economic losses for fish farmers. Temperature does not only affect salmon physiology but may also exacerbate negative impacts by pathogens, disease dynamics and parasites [403].

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[399] DNV GL 2019
[400] Frölicher et al. 2018
[401] Burke et al. 2020
[402] Oliver et al., 2017; Wade et al., 2019
[403] Vollset et al. 2021

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Oxygen

The solubility of oxygen in water is temperature and salinity dependent. It decreases with increasing salinity and increasing temperatures. The oxygen demands of the salmon increase with increasing temperatures due to a higher metabolic rate [404]. High sea temperatures are therefore problematic as they result in hypoxic conditions due to combined effects of decreased oxygen solubility and increased metabolism of the fish in sea cages. Remen et al. reported elevated levels of the stress hormone cortisol, and reduction in feeding and growth when oxygen levels fell below 60 % at 16 °C [405]. The hypoxia tolerance threshold for Atlantic salmon increases with temperature. At 18 °C the limiting oxygen saturation is reached already at 55 % oxygen saturation [406].

Extreme weather events and increased precipitation

Simulations indicate an increase in frequency and intensity of storms at high latitudes towards the end of the century [407]. Storms and waves are a severe threat for the fish farming industry.

Wind and waves can damage infrastructure, cause welfare problems for the fish and also pose a severe risk for the environment. In 2020. nearly 50 000 farmed Atlantic salmon escaped in Scotland after a storm had damaged the mooring ropes and more than 30 000 fish died in the incident [408]. Escaped domesticated salmon are a threat for wild salmon populations as they may exert negative effects to the genetic pool during interbreeding [409] .

The projected change towards milder winters and overall increased precipitation will increase freshwater inflow to the fjords. This may have both positive and negative consequences. The parasitic sea lice (*Lepeoptheirus salmonis* and *Caligus* sp.) do not tolerate fresh water and increased freshwater inflow may aid to reduce sea lice pressure. On the other hand, river-runoff

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[404] Remen et al., 2016
[405] Remen et al., 2012
[406] Remen et al., 2013
[407] Knudsen and Walsh 2016
[408] Fisheries Management of Scotland 2020
[409] Glover et al. 2020

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will carry organic material from sediments into the fjord, and the resulting higher levels in phosphorous and nitrogen host a risk for conditions that benefit the development of harmful algae blooms [410].

Ocean acidification (pH)

About one third of the anthropogenic CO_2 emissions has been taken up by the ocean [411]. The uptake of CO_2 has resulted in a decrease in pH by 0.1 since pre-industrial times [412] and a further decrease to values between 8.05 and 7.75, depending on different greenhouse gas emission scenarios, is projected for the end of the century [413]. Ocean acidification will not directly impact salmon aquaculture as Atlantic salmon cope well at a pH down to 6.2 [414]. Yet, ocean acidification will affect the marine ecosystem and will reduce the potential for cultivation of lower trophic species such as sea urchins and bivalves that are more vulnerable acidification [415]. The red king crab (*Paralithodes camtschaticus*) has a high economic value for local fisheries in the Varanger hub and studies indicate increased mortality of this species at pH 7.5 and lower [416].

5.3.1.2 Biotic factors

Disease, pathogens and parasite dynamics in a changing climate

Higher temperatures may lead to an increased susceptibility of Atlantic salmon to pathogens. For example, Atlantic salmon is more vulnerable to amoebic gill disease caused by the protist *Neoparamoeba perurans* at higher temperatures [417].

On the other hand, milder winters, may reduce the risk for infections with coldwater pathogens such as *Moritella viscosa*, causative agent of winter ulcers or *Aliivibrio salmonicida*, responsible for cold water vibriosis [418].

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[410] Gilbert 2020
[411] Gruber et al. 2019
[412] Caldeira and Wickett 2003
[413] Kwiatkowski et al. 2020
[414] Kroglund et al. 2007
[415] Stewart-Sinclair et al. 2020
[416] Long et al. 2013
[417] Benedicenti et al. 2019
[418] Sae-Lim 2017

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Sea lice infestations are considered the biggest problem faced by the salmon farming industry today. High infection pressure of *Lepeophtheirus salmonis* and species of the genus *Caligus* at farm sites pose a major threat to wild salmon populations and lead to welfare and health problems of farmed salmon [419]. Delicing procedures cause environmental issues, welfare issues for the fish, and considerable costs for the fish farmer [420]. High water temperatures accelerate the life cycle of the salmon lice substantially. A recent study reported the development time of females from copepodid to adult at different temperature regimes and showed a reduction from 72 days post-infection at 6 °C to 13 days post-infection at 21 °C [421]. In another study it has been modelled that the infection pressure will increase by two given a 2 °C increase in the temperature range from 9 to 11 °C) and even stronger effects (4.4-fold increase) in the lower temperature range (5 to 7 °C) [422]. Furthermore, weakening of the Atlantic-Pacific boundaries can lead to introduction of pacific sea louse species through Pacific fish species [423].

New parasite species and diseases are most certainly going to cause problems for the sector. Today, sea lice pressure in the Varanger fjord is low. In 2022, the production zones West-Finnmark and East-Finnmark are two out of eight production areas that were granted further growth. Also, the southernmost production area 1, where Egersund is located, got green light for further growth, this area is located close to production areas with high sea lice densities (production areas 2 and 3), and sea lice pressure may restrict future growth in the coming years. Several reports predict that fish farming activities will be shifted northwards [424]; this together with increasing temperatures will likely lead to an increased sea lice pressure also in the north, given that the sea lice problematic is not resolved by other measures, for example production of fish that are resistant to sea lice through genetic engineering.

Changes in the marine ecosystem

Sustainable seafood production is highly dependent on a functioning marine ecosystem. Abiotic and biotic changes in the farm environment may affect fish farming both directly and indirectly. Eutrophication in combination with higher water temperatures may increase the risk for incidents of harmful algae blooms or jellyfish invasions [425]. Harmful algae blooms have caused

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[419] Vollset et al. 2021
[420] Liu et al. 2014
[421] Hamre et al., 2019
[422] Sandvik et al., 2021
[423] Sandvik et al., 2021
[424] Vollset et al. 2021
[425] Karlson et al., 2021

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single mass mortality (8 million dead salmon in 2019) events in salmon farms in Northern-Norway (Lofoten and Tromsø area) in the past. Furthermore, the reports on harmful jellyfish blooms have increased during the past years [426]. Damage to gills and skin of Atlantic salmon caused by jellyfish can lead to severe lesions, and in worst case mortality [427]. Smaller wounds caused by jellyfish stings are suspected to become ports for pathogens and jellyfish may be carriers of pathogens. For example, an invasion of the jellyfish *Dipleurosoma typicum* coincided with a tenacibaculosis outbreak in a fish farm located in Ryggefjord, ca. 200 km north-west of the Varanger area [428].

The underlying causes of harmful algae blooms and jelly fish invasions are still poorly understood, and it has been argued that the perception of an increased frequency of harmful algae bloom during the past years could be explained by the aquaculture-related intensification of monitoring procedures [429]. Yet, there is a strong scientific consensus that future anthropogenic activities are going to increase the risk for harmful algae blooms and better early warning systems are necessary to safeguard marine food production [430].

5.3.2 Indirect impacts of climate change on the fish farming hubs

5.3.2.1 Feed production as bottleneck

In 2016, 25 % of the salmon feed ingredients came from marine resources, 71% were of plant origin and 4 % were from other origins [431]. The need for fish feed illustrates how the arctic fish farming hubs are directly connected to global fisheries and agriculture. A recent study reported that the average global yield of soyabeans, a major ingredient of salmon feed, has decreased by 4.5 % from 1980 to 2010 [432]. It is projected that, under RCP 8.5, over 90 % of the world’s population will be affected by losses of food production from agriculture and fisheries, with the strongest impacts in the tropical regions [433].

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[426] Bosch-Belmar et al., 2020
[427] Baxter et al., 2011
[428] Halsband et al., 2018
[429] Hallegraeff et al. 2021
[430] Glibert 2020
[431] Aas et al. 2019
[432] Iizumi et al. 2018
[433] Thiault et al. 2019

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5.3.2.2 Governance

In Norway, new aquaculture licenses are distributed according to a traffic light system, where green light indicates further growth of salmon farming at sea [434]. The sea lice situation in the south-western areas and Mid-Norway combined with more unfavorable culturing conditions due to increasing water temperatures will likely shift the mariculture northwards enabling economic growth and providing new jobs in the Varanger area. An intensification of fish farming in the north will increase the pressure on an already vulnerable ecosystem and can lead to conflicting interests among fish farmers, fishermen and the tourism industry. The projected intensification of fish farming will require the necessary changes in logistics including viable infrastructure for product processing and transportation. The Norwegian government is following the EU climate regulations towards a zero emissions society. To reduce greenhouse gas emissions from the transport sector, the government has issued a demand for low-and zero-emission vessels used by the aquaculture and fisheries sector that is being stepwise introduced from 2024 [435]. These indirect consequences of climate change must be considered in future-scenario planning [436].

5.4 Forestry

Forests are under a constant change due to several biotic and abiotic factors. Abiotic factors like temperature, humidity, precipitation, wind and soil properties essentially determine the production capability of forest ecosystems but can also cause several types of disturbances. Biotic factors like species structure and species interactions also constantly modify forest ecosystems and can also cause disturbances in forest ecosystems. Abiotic and biotic factors often interact, and the ecosystem dynamics is a consequential series of these interactions. From the economical point of view, different disturbance factors become damage agents when they cause considerable loss to forest owners via killed trees, reduced growth of trees or impaired quality of expected tree-based products. In silviculture, abiotic and biotic damage agents are controlled via different measures but cannot be totally eliminated. Both abiotic and biotic damage agents are connected to climatic factors and thus their importance in forestry can change along with predicted climate change and associated climatic factors. This chapter shortly reviews the effect of climate change on the most important damage agents from the point of view of forestry in ArcticHubs project hub areas in Finland, Sweden, and Norway.

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[434] Grefsrud et al. 2021
[435] Ministry of Climate and Environment (Norway) 2021
[436] Froehlich et al. 2018

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5.4.1 Heat and drought effects

The rise of temperature in all seasons is one of the predicted consequences of climate change. As the growth of trees is highly dependent on temperature the rise of temperature in the growing season is predicted to increase the growth of trees and thus expected yield of forests [437]. However, the combination of extremely high temperatures and drought can have detrimental effects on trees as the deficit of water leads to reduced growth of trees or can eventually kill trees. Among the most important tree species in boreal forests, Norway spruce (*Picea abies*) is especially vulnerable to drought. Norway spruce grows naturally in fertile soils, but in recent decades it has been regenerated also on less fertile soils due to fear of cervid damage to Scots pine (*Pinus sylvestris*) [438]. Less fertile soils are often moraine, which is permeable to water and thus the water content of soil is low. The predicted temperature increase combined with drought is thus especially detrimental to spruce in moraine soils. However, according to climate change scenarios, the effect of drought on spruce is the most serious in southern Finland [439]. In the ArcticHubs hub areas in northern Finland, the effect of drought in spring and summer does not increase during the coming couple of decades but starts to increase after 2040's. The effects of heat and drought on forestry in ArcticHubs areas in all countries are thus probably minor.

5.4.2 Pest outbreaks

Several invertebrate species inhabit trees and they have an important role in forest succession dynamics. The population of some species can increase manyfold after climatically induced disturbance or other stress factors making them potential pests from the point of view of forestry [440]. Some species show somewhat regular outbreaks, while some outbreaks are eruptive, and some have sustained effects on trees and forest ecosystems. Because the development of insects is highly dependent on temperature, increasing temperatures due to climate change has been predicted to enhance the reproduction capability also of several pests. However, the population dynamics of invertebrate species is dependent also on several non-climatic factors and, therefore, it is not straightforward to distinguish the effects of climate change from other factors like forestry-related changes in forest ecosystems [441]. The most important invertebrate forest pests in northern boreal forests are defoliators and bark beetles (Scolytidae spp.).

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[437] Lehtonen et al. 2020
[438] Huuskonen et al. 2021
[439] Lehtonen et al. 2020
[440] Neuvonen & Viiri 2017
[441] Neuvonen & Viiri 2017

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5.4.2.1 Defoliators

In northern boreal forests, the most common defoliators on birch (*Betula* spp.) are geometrids as autumnal moth (*Epirrita autumnata*) and winter moth (*Operophtera autumnata*); see section 4.1.2. Both species occur throughout boreal forests, but they have had the largest outbreaks in the northernmost parts of Finland, Sweden and Norway. The largest outbreaks of autumnal moth in the 1960s led to the death of mountain birch over hundreds of square kilometres in the northernmost part of Finland [442]. Less severe outbreaks by autumnal moth followed in 1990s and mid-2000s [443]. Outbreaks of winter moth have not been that common than those of autumnal moth, and the first large defoliation was recorded in the beginning of 2000s, which led to large-scale mortality [444]. The defoliation from winter moth completely changed ecosystem composition and function.

Low winter temperatures have suppressed the reproduction of both defoliator species because they overwinter as eggs which die at temperatures below −36 °C. Predicted increase in winter temperatures will reduce the number of winters with extreme low temperatures. Thus, outbreak area will expand [445]. Although mountain birch forests are not important from a forestry point-of-view, they are important for local communities as reindeer herding pastures, as wood supply, and as areas rich in bilberry (*Vaccinium myrtillus*) and lingonberry (*V. vitis-idaea*), which are picked in large quantities. Therefore, the impact of climate change on local cultures and livelihoods will be considerable through the warming-induced increase in forest pest outbreaks [446].

There are several species defoliating Scots pine (*Pinus sylvestris*), but so far, only three of these species have been important as pests in northern boreal forests. These are European pine sawfly (*Neodiprion sertifer*), common pine sawfly (*Diprion pini*) and pine looper (*Bupalus piniarus*). Of these, pine looper has caused only local and rather limited damage. Typical feature of the pine defoliator outbreaks is that they occur on drier and less fertile soils, i.e., graded sandy soils [447].

The life cycles of European pine sawfly and common pine sawfly differ in that *N. sertifer* overwinters as eggs in Scots pine needles whereas *D. pini* overwinters as cocoons in soil. Therefore, also the impacts of climatic factors on these species differ. Winter temperature below

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[442] Seppälä and Rastas 1980
[443] Ruohomäki et al. 1997, Kopisto et al. 2008
[444] Jepsen et al. 2016, Vindstad et al. 2022
[445] Virtanen et al. 1998
[446] Neuvonen & Viiri 2017
[447] Nevalainen et al. 2015

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−36 °C is detrimental to *N. sertifer* eggs and, therefore, if the frequency of cold winters decreases due to climate change, outbreaks will be more common in future [448]. The predictions also show that the range of outbreaks expands to northernmost Finland. As *D. pini* overwinters as cocoons in soil, an increase in winter temperature will not affect its reproduction in a similar way as for *N. sertifer*.

Scots pine commonly recover from defoliation because *N. sertifer* mostly defoliates older shoots, while fresh shoots remain intact. If severe defoliation runs of several years, parts of trees can die, but the most common effect is reduced growth. Defoliation by *D. pini*, however, is more detrimental to Scots pine, because it also defoliates fresh shoots. Multi-year defoliation result in increased mortality of trees. In the ArcticHubs hub forested areas, i.e., mostly northern boreal forests, the frequency of outbreaks is projected to increase three- to five-fold [449]. However, the impact on forestry will probably be limited and comparable to the present situation in more southerly forests. In southern parts of Finland there have been instances of large-scale defoliation leading to retarded growth rates, but mortality has only occurred very locally.

5.4.2.2 Bark beetles

C. 60 species of bark beetle (Scolytidae spp.) occur in boreal forests of northern Finland, Norway and Sweden, and some of them can cause severe damage to coniferous trees, especially to Norway spruce [450]. The most severe pest is spruce bark beetle, *Ips typographus*, which has killed trees in large areas in several European countries [451]. The range of spruce bark beetle extends to northern boreal conifer forests.

Spruce bark beetle needs fresh phloem under bark for brood development. Thus, the outbreaks have typically followed after large disturbances (e.g., windthrows) and stress factors (e.g., extremely dry and warm summers) [452]. If the population level is high, spruce bark beetle can also attack healthy spruce. The amount of damage to spruce increases along stress and damage gradients, and thus, the magnitude of spruce bark beetle damage is strongly coupled to climatic factors. The amount of spruce bark beetle damage in Finland has historically been at low levels as compared to other Nordic countries. From the beginning of 2010s, however, the amount of

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[448] Virtanen et al. 1996
[449] Virtanen et al. 1996
[450] Neuvonen & Viiri 2017
[451] Hlásny et al. 2021
[452] Hlásny et al. 2021

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damage has increased in southern Finland [453]. This increase is partly attributed to high amount of fresh windthrown spruce in forests, but also to warm and dry summers during this same period. Extreme heat events and storm events are expected to occur more frequently (see section 4.2). Thus, conditions suitable for spruce bark beetle outbreaks are likely to increase during the next decades, at least in the southern boreal forests of the Nordic countries.

Spruce bark beetle damage in Finland have so far not affected forestry despite some large windthrow areas containing several hundreds to some millions of cubic meters of windthrow trees [454]. The proportion of trees either windthrown or killed by spruce bark beetle has corresponded to only about 1 % of the annual forest harvest in Finland. Spruce bark beetle damage in the northern boreal forests above 65 °N, and thus within the ArcticHubs study region, have been scarce and of minor impact to forestry. According to climate change scenarios, spruce bark beetle damage in northern boreal forests probably remain minor also in future despite increasing temperatures [455]. Another reason for low impact of spruce bark beetle damage on forestry and tree markets is due to the fact that the capacity of tree harvesting logistics and wood processing industry are capable of effectively harvest damaged trees.

5.4.3 Windbreak and winter-related damage

During the period from 1978 to 2019 there were a total of 15 large windthrows in Finland [456]. Of these, the eight most remarkable windthrows occurred between 2001 and 2013. The amount of destroyed trees in these storms totalled about 22 million m^3. Minor windthrows occur almost every year, and the volume of windfallen trees in each year has been between 0.1 and 1.1 million m^3. The only major windthrow in the ArcticHubs area of northern Finland occurred in 1982, which felled about 3 million m^3. Windthrows are, thus, more common in central and southern Finland.

Over a long timescale, major storms causing windthrows have, on average, occurred once every 10-15-years [457]. There has been a significant increase in storm frequency during the last decades [458]. Projections regarding future high wind speeds are variable [459]. In all scenarios, the predicted change has been relatively low, between −3 and +2 %. Although the change in the frequency of storms might not be radical, single heavy storms can cause remarkable damage to forests. As

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[453] Neuvonen & Viiri 2017
[454] Viiri et al. 2019
[455] Lehtonen et al. 2020
[456] Viiri et al. 2019
[457] Lehtonen et al. 2020
[458] Jokinen et al. 2015
[459] Lehtonen et al. 2019

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an example, the storm “Gudrun” felled ca. 70 mill. m^3 of trees in Sweden, causing severe harvesting challenges; resulting in major bark beetle damage [460].

From the forestry point-of-view, there are several factors that alleviate the knock-on effects of windthrows; forest industries use large amounts of wood annually and they usually can handle also windthrown trees by means of the extensive forest road network, the high number of harvesters, and the efficient harvesting logistics enabling the harvest of felled trees. Moreover, in Finland and Sweden, legislation oblige forest owners to harvest windthrows and other damaged trees from forest if they exceed a certain amount of timber.

To conclude, despite their relatively low frequency, large windthrows will probably occur at high latitudes covering the ArcticHubs forest hub areas. Extremely high amounts of windthrows will affect wood markets due to excessive amounts of accessible wood coming to market [461]. The effect on the wood market will highly depend on the general market situation, season, and the amount of different wood species.

Three ungulate species occur in the ArcticHubs forest hub areas. These are moose (*Alces alces*), reindeer (*Rangifer tarandus*) and roe deer (*Capreolus capreolus*). Of these, only moose can cause major damage to trees. In summer, moose utilize several species of plants, but in winter, a moose's diet consists mainly of woody species [462]. In winter, a moose's diet consists mostly of Scots pine, but also birch (*Betula* spp.), willows (*Salix* spp.), aspen (*Populus tremula*), juniper (*Juniperus communis*), planted Norway spruce (*Picea abies*) and rowan (*Sorbus aucuparia*) are regularly consumed. In terms of quantity, moose consume mostly Scots pine in winter.

Moose cause damage to trees by breaking leader shoots and the main stem, by browsing lateral shoots and by stripping bark [463]. Most of the damage occurs in winter, but summertime damage can also be substantial [464]. Consequently, especially smaller plants can die, but browsing for the most part causes defects in the tree stem and reduces growth or impairs the technical quality of saw wood.

In Finland, moose damage to forest plantations has been recorded on more than 900,000 ha (= 9,000 km^2) during the 2010s, on which severe damage was recorded on up to 100,000 ha. The

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[460] Lehtonen et al. 2019
[461] Viiri et al. 2019
[462] Cederlund et al. 1980
[463] Bergqvist et al. 2001
[464] Bergqvist et al. 2013

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majority (75%; 85,000 ha) of damage occurred in Scots pine-dominated stands. This corresponded to ca. 22 % of all Scots pine plantations [465]. In Sweden, moose damage was found in 12-15% of Scots pine plantations during the period from 2003 to 2013. Also in Norway, moose and other ungulates have been among the most severe damage agents to forestry; moose has been estimated to cause a loss of 1.5 to 3.7 million euros annually.

The thickness of snow affects moose damage; during deep snow cover moose move little to save energy and concentrate their browsing on small areas, mostly Scots pine-dominated seedling stands. Under such conditions, remarkable damage to trees occurs [466]. The recent increase in midwinter snow depth (see section 3.1.2), which will prevail into the near future (see section 3.3), may lead to more concentrated habitat use of moose and increased damage to trees also within the ArcticHubs forest areas [467]. However, moose populations are heavily regulated, and regional targets for population size also consider the development of moose damage. Therefore, although climate change can have some effects on moose ecology, it is probably not among the most important factors for future forest development.

Snow accumulation frequently damage tree crowns [468]. In areas expecting more snow, such type of damage to trees may increase. However, declining snow will be the predominant trend, especially at decadal time scales (see section 4.3). Instead, damage related to reduced snow cover on the ground and increasing frequency of temperature fluctuations around the freezing point will be causing increasing winter stress to trees (see also section 3.4.1). Reduced snow cover can result in deeper soil frost, while periods of milder temperature regimes stimulate to physiological activity. This combination of these types of events results in frost drought to conifers, which often becomes visible as red belts in the forested landscape [469]. Such events will reduce the quality of timber (Figure 5.2).

Moreover, as climate becomes warmer, disturbed hibernation and increasing respiration during dark winter periods will become an increasing challenge for northern conifers [470]. Respiration increases with increasing winter temperature, because cells are becoming activated and will need to do maintenance respiration [471]. Carbon consumption during maintenance respiration can equal, or even exceed, carbon consumption allocated to growth during the growing season. Maintenance respiration is instigated at below-freezing temperature; at −2.4 °C respiration rate

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[465] Nikula et al. 2020
[466] Matala 2020
[467] Matala 2020
[468] Korhonen et al. 2021
[469] Langlet 1929, Jalkanen 1997, Solheim & Venn 2003, Bjerke et al. 2014
[470] Ögren et al. 1997
[471] Amthor 1984, Ryan 1995

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is approximately half of the rate at +5 °C [472]. Loss of carbohydrate reserves has numerous negative consequences for plants, in particular evergreen plants. It leads to reduced growth rates in the early growing season [473]. More serious is that loss of carbohydrates leads to dehardening, i.e., the plants' cold tolerance is reduced, because intracellular carbohydrates act as antifreeze solution [474]. Northern and continental species are more vulnerable to increasing winter temperatures than southern and more oceanic species [475]. Crawford [476] explains this: northern and continental species are adapted to quickly respond to increasing temperatures to make use of the whole growing season, whereas for southern and more oceanic species, a temperature increase is not an indicator that plants can trust for assessing whether the true growing season is initiated. Thus, the response rate to increasing temperature is slower in southern and oceanic species. To conclude, the climate change-induced increase in oceanicity of interior parts of Finland, Sweden and Norway will result in challenging winter conditions for Norway spruce and Scots pine, and this will have major implications for quality of timber with impacts on the economy of forestry in these countries.

Figure 5.2. Planted Norway spruce trees dead due to a winter with frost drought. These trees were planted in an oceanic deciduous forest (Senja, Norway). The deciduous trees were not visibly affected by the frost drought. Photo: Jarle W. Bjerke ©

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[472] Ögren et al. 1997
[473] Stewart & Bannister 1973, Skre 1995, Skre & Nes 1996
[474] Ögren 1996, Crawford 2000, Bokhorst et al. 2018
[475] Stewart & Bannister 1973, Crawford & Palin 1981
[476] Crawford 2000

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5.5 Mining

Climate change has a range of impacts on mining activities in the Arctic. On one hand, retreating glaciers and declining sea ice extent open up more opportunities for mineral exploration and extraction; on the other hand, thawing permafrost and increasing rainfall potentially increase challenges with mining operations and the stability of mine tailings dams and other mine infrastructure as well as increase potentially toxic run-off from mining sites.

5.5.1 Glacier retreat and decline of sea ice extent

Glaciers in Greenland have been retreating and thinning for decades [477], and this is expected to continue. As a result, more ice-free land is becoming available for mineral exploration and extraction. The Nordic geological surveys have recently published a report [478] on the ‘unexploited economic potential’ in the Nordic bedrock for mineral exploration of ‘critical raw materials’ [479] that are essential for technologies needed for the green energy transition. They concluded that Greenland is relatively unexplored compared to other Nordic countries but has great potential, particularly for those metals that are most in demand such as rare earth elements (REE). This has prompted a new focus on geological and geophysical research projects [480] and attracted major interest in mineral exploration with a number of companies starting new exploration activities in Greenland in 2022 [481].

Similarly, the declining sea ice extent will facilitate exploration and exploitation of natural resources in the Arctic oceans, in particular seabed mining [482]. As result of the increasing interest in seabed mining in the Arctic, the Norwegian government has recently initiated an impact assessment as part of the opening process for mineral exploration on the Norwegian continental shelf and has funded several research programmes into the geological, technological and environmental aspects of (deep) sea mining and the mapping of mineral resources on the continental shelf [483].

5.5.2 Permafrost thaw

One of the consequences of permafrost thaw is a thickening of the active layer, which can cause subsidence, slope instability and changes in hydrology. These permafrost hazards increase the

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[477] King et al. 2020, The IMBIE Team 2020
[478] Eilu et al. 2021
[479] European Commission et al. 2020
[480] e.g. Jackisch et al. 2022
[481] Wenger 2022, Henriques & Böhm 2022, Nuttal 2022
[482] Mendez, 2009, Solli, 2014, Prytz et al, 2018
[483] Ministry of Petroleum and Energy of Norway 2021

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risk of damage to infrastructures such as buildings, roads and pipelines [484]. and can also impact the stability of mining-specific infrastructures such as waste rock piles, mine tailings and tailings dams [485]. Although these risks are highest in Russia and North America, where significant damage to infrastructures are already reported, the ArcticHubs locations in Greenland and Svalbard are also at risk. In permafrost regions, including Greenland and Svalbard, mine tailings and waste rock piles are often frozen and chemical reactions such as oxidation are limited under these cryogenic conditions. When mine tailings thaw, the now available water can interact with the tailings leading to weathering, leaching and pollutant transport, particularly in tailings containing sulphides such as iron and copper ores [486]. Degrading permafrost is thought to have contributed to the failure of a mine tailings dam from a gold mine in eastern Russia causing the spillage of large quantities of toxic sediments which polluted the local river ecosystems, fisheries and a nearby town [487]. Engineering solutions to prevent leakage and damage to infrastructures do exist, but the costs can be high. However, in general, permafrost thaw related damage or risk of damage to infrastructure is much less in Greenland and Svalbard than in North America or Russia due to the ground properties and construction types and maintenance [488].

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[484] Hjort et al. 2018, 2022
[485] Yurkevich et al. 2021
[486] Yurkevich et al. 2021, Søndergaard & Mosbech 2022
[487] Glotov et al. 2018
[488] Hjort et al. 2022

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Figure 5.3. Aitik copper mine, near Gällivare, Sweden. Photo: Corine Davids ©

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6 Supporting information

6.1 NDVI trends for hubs

Trends of MODIS Maximum NDVI (MaxNDVI) and summed NDVI (SumNDVI) over the DOY-period 145-241 for the various hubs in the Nordic countries. Significant trends in *italics*. SumNDVI is based on 6-day averages for the June-August period. n.s. = not significant.

	Mean MaxNDVI	**Trend MaxNDVI**	***p*-level Trend MaxNDVI**	**Mean SumNDVI**	**Trend SumNDVI**	**Trend SumNDVI**
Hub	2000-2021	2000-2021	2000-2021	DOY 145-241	2000-2021	2000-2021
Kemijärvi	0.74	*0.02*	<0.05	4.84	*0.26*	<0.01
Kemi	0.80	0.00	n.s.	5.17	*0.14*	<0.05
Inari	0.71	*0.06*	<0.01	4.52	*0.44*	<0.01
Kittilä	0.77	0.02	n.s.	4.95	*0.25*	<0.01
Jokkmokk	0.76	0.01	n.s.	4.90	*0.30*	<0.01
Gällivare	0.75	0.01	n.s.	4.75	*0.02*	<0.05
Khibiny	0.58	*0.04*	<0.01	3.39	0.29	n.s.
Kovdor	0.75	*0.04*	<0.01	4.83	*0.39*	<0.01
Kautokeino-Kvalsund	0.66	0.02	n.s.	3.81	0.16	n.s.
Varangerfjord	0.62	*0.04*	<0.01	3.59	*0.30*	<0.05
Gran sameby Winter	0.76	0.01	n.s.	4.94	*0.22*	<0.01
Grans sameby Summer	0.72	*0.04*	<0.01	3.95	0.26	n.s.
Egersund	0.74	0.01	n.s.	4.85	0.07	n.s.

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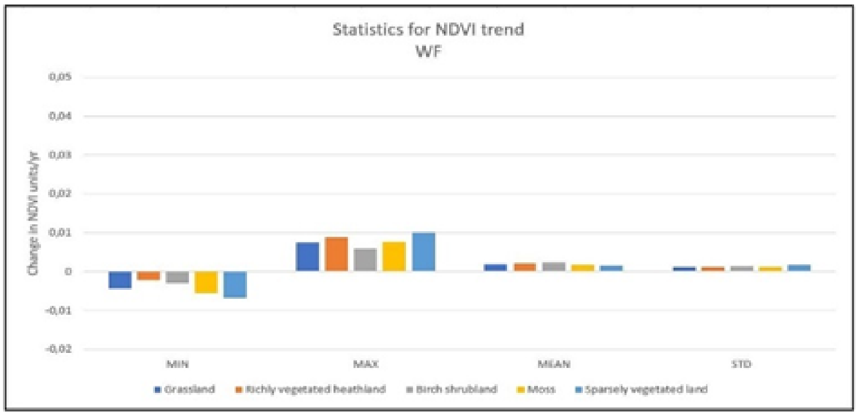
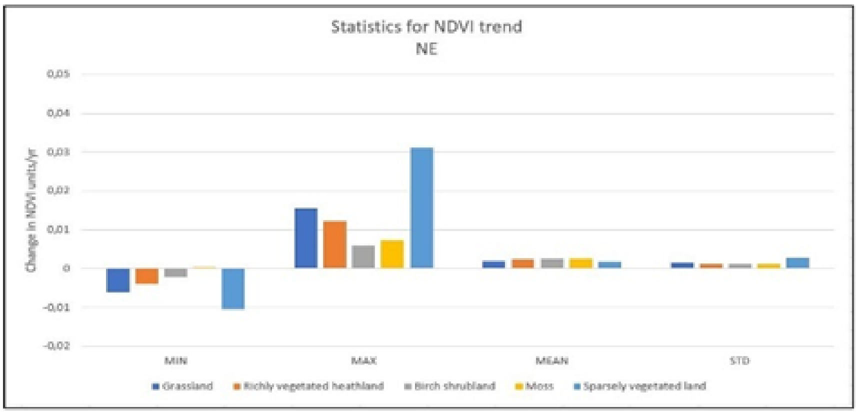
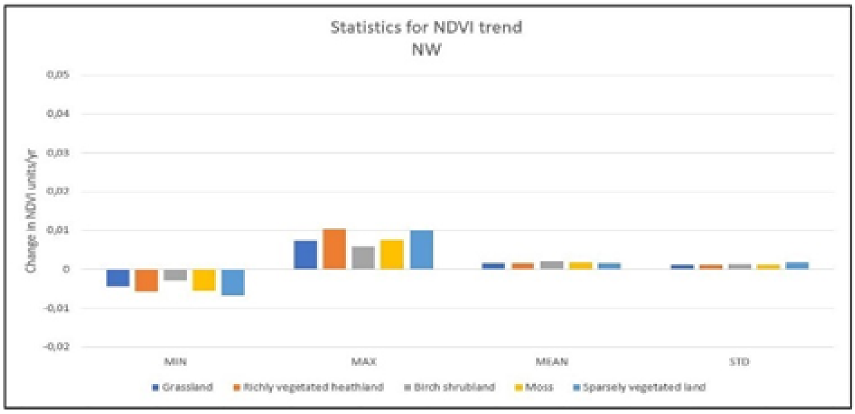
6.2 NDVI statistics for Iceland

Bar graphs showing the statistical results (min, max, mean, standard deviation) for the gain coefficient broken down by region in Iceland and land cover type.







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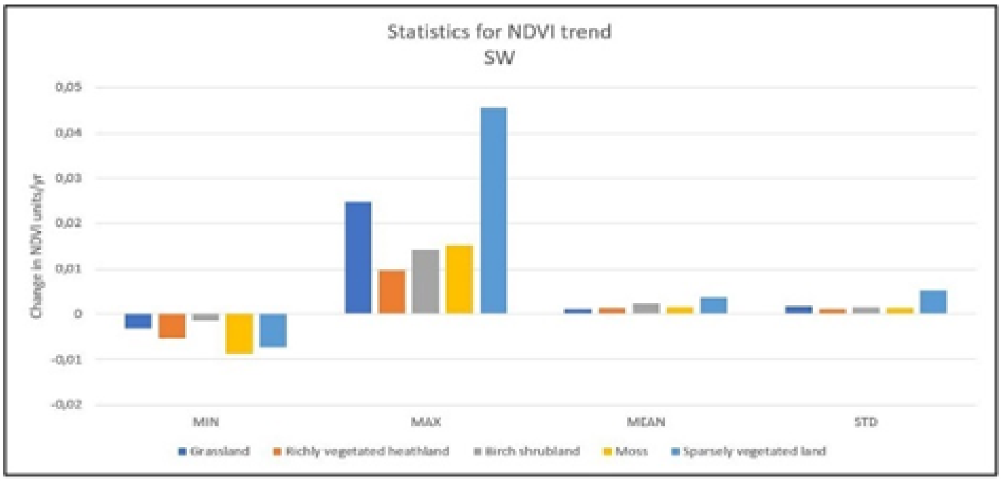

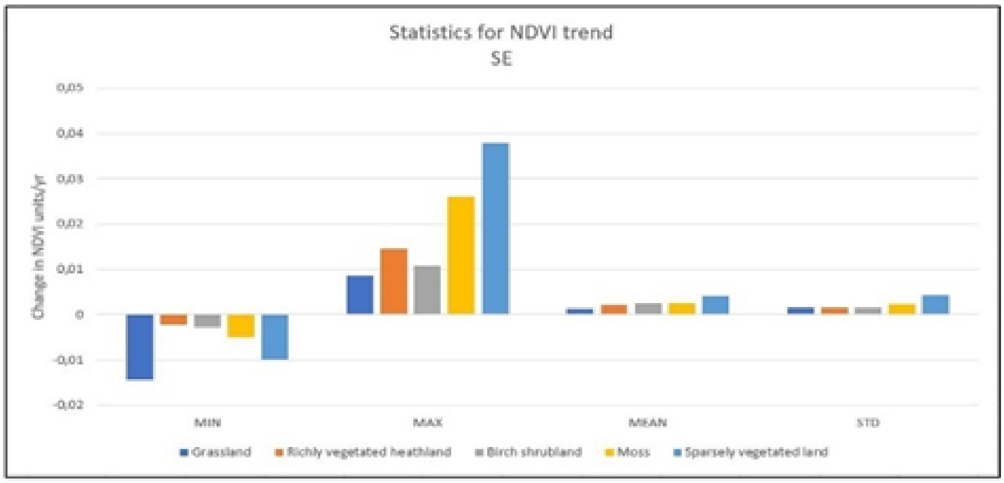

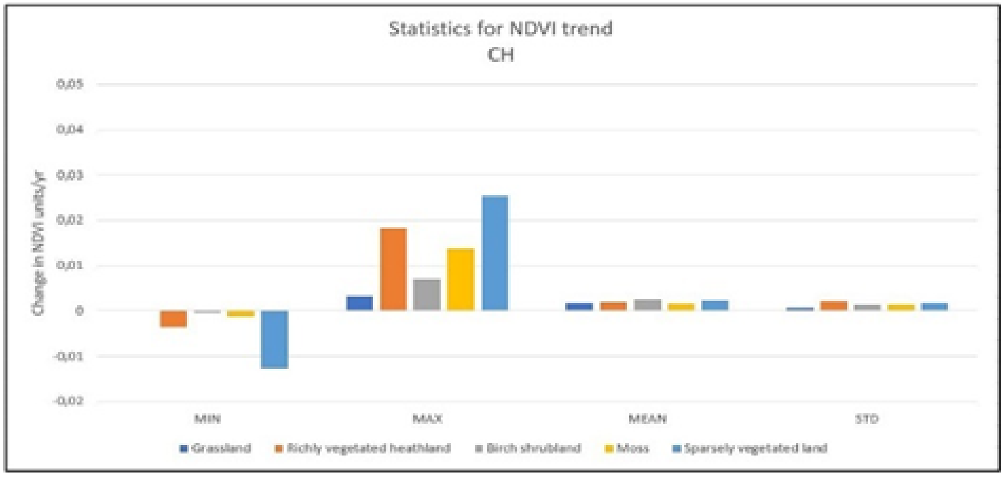

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6.3 Changes in growing season in the Kvalsund area: impacts on reindeer grazing

This report does not go into detail at hub-level on every aspect. However, here we dive into one specific hub to further illustrate how year-to-year changes in growing season impact reindeer grazing conditions. Within the Kautokeino-Kvalsund indigenous hub, we selected a 2 km × 2 km polygon for analyses of possible impacts on the grazing system due to changes in growing season parameters. The polygon is within the reindeer district 22-Fiettar and covers parts of the valley Kvalsunddalen with surrounding altitudes up to 200 m a.s.l. (Figure S1). It is an important area, since it is grazed and used by reindeer both at spring, summer and autumn, it has a gathering area, and parts of the area is also within herding routes [489]. Hence, the reindeer need to utilize the changes in the growing season. The area is also only a few kilometers northwest of the Nussir ASA's suggested copper mine, and the planned mining activity will need to adapt to the reindeer's seasonal use of the area. Further, the timing of when the area is used also impacts and puts pressure on other land users and between different herding groups.

Overall, the MODIS satellite data from March 2000 until September 2022 shows no significant trends in growing season parameters, but shows large variability between the years, where years with warm spring and summer can be used as example of near-future normal years according to climatic scenarios.

If the reindeer migrate into the area when it is still snow-covered, it has access only to limited forage resources; it will need to graze on lichens and prostrate shrubs on the snow-free ridges. The area (red square on Figure A1) is on average free of snow 12 May (mean date for the period 2000-2022), although some smaller spots become snow-free much earlier. Late snowmelt occurred in the years 2000 (5 June) and 2017 (4 June). Early snowmelt occured in 2015 (24 April) and 2004 (25 April). Hence, there is more than 40 days between the very late and very early snowmelt. When the first sprouting occurs, more and better forage resources become available. On average, sprouting starts on 31 May. Sprouting is earlier in the lowland and on ridges within the study area, and much later in snowbeds.

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[489] Eira et al. 2020

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Figure S1. Kvalsund area in Finnmark, north Norway. The maps show herding routes. Growth season parameters is extracted from the red square.

A more uniform green-up, defined as unfolded leaves on dwarf birch, initiates a period when food is very easily available, and the food is nutrient-rich and there are no disturbing insects. The mean (2000-2022) date for green-up is 6 June. The latest green-up occurred in the years 2000 (1 July) and 2020 (17 June). In both years, this very belated green-up was a result of extreme snow amounts in winter and late thaw in spring. The correlation between green-up date and May temperature is high and significant ($r^2 = 0.41$, $p < 0.001$, $n = 23$). Skipping the first year of the time series (2000), increases the correlation to $r^2 = 0.58$, showing that lot of snow with corresponding late snowmelt delayed the general onset of growth that year. The earliest onset of growth was 22 May (Year 2006), which is 40 days earlier than in the extreme late year 2000. The temperature data used is from the SeNorge gridded dataset [490].

Time of peak NDVI is the time of the year with the highest biomass. On average, for the study area, peak is reached on 26 July. Forage quality of most plant species start to decrease from peak time.

Time-integrated NDVI (TI NDVI) values indicate the total available forage resources each year and useful for assessing the number of reindeer that can graze within a particular area. TI NDVI for the period from 25 June to 25 July correlates well with mean June-July temperature (r^2 =

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[490] Lussana et al. 2018

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0.26, $p = 0.012$, $n = 23$). Albeit not statistically significant ($p = 0.21$), there is a tendency to increasing TI-NDVI for the 2000-2022 period (Figure S2). The lowest TI-NDVI occurred in the year 2000 when onset of growth was very late and June-July temperature was below average. Further, the year 2012 was very cold and with low TI-NDVI, a year elucidated in detail in Bjerke et al. [491]. The highest annual productivity, and hence, lots of available reindeer forage, occurred in the most recent summer in the time series, 2022. This summer had a TI-NDVI value of 20.7, as compared to only 16.0 in the year 2000 (Figure S2). The last seven years have all had TI-NDVI values above the 2000-2022 average.

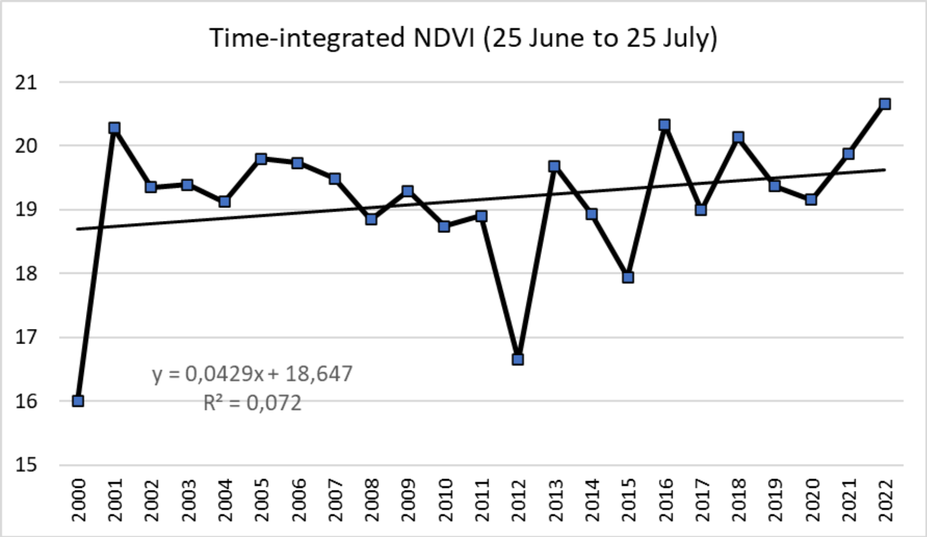

Figure S2. Time- integrated NDVI (25 June to 25 July) for the Kvalsund area (red square in Figure S1).

Autumn colouring indicate less available forage resources. Time for yellowing of leaves, defined as more than 50 % yellow leaves on birch, occurs on average 13 September, with a very early coloring in the year 2011 (27 August) and late in 2017 (24 September). Although green grass and herbs are still found in snowbeds and wetlands after the general yellowing of leaves, the grazing value of the area rapidly decrease in autumn.

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[491] Bjerke et al. 2014

7 References

Aalto J, Pirinen P, Kauppi PE, Rantanen M, Lussana C, Lyytikáinen-Saarenmaa P & Gregow H (2022) High-resolution analysis of observed thermal growing season variability over northern Europe. *Climate Dynamics* 58: 1477-149. https://doi.org/10.1007/s00382-021-05970-y

Aarrestad PA, Bjerke JW, Follestad A, Jepsen J, Nybø S, Rusch G & Schartau AK (2015) Naturtyper i klimatilpasningsarbeid. Effekter av klimaendringer og klimatilpasningsarbeid på naturmangfold og økosystemtjenester. *NINA Rapport* 1157. 98 pp. Norwegian Institute for Nature Research, Trondheim. https://www.nina.no/archive/nina/PppBasePdf/rapport/2015/1157.pdf

Aas TS, Ytrestøyl T & Åsgård T (2019) Utilization of feed resources in the production of Atlantic salmon (*Salmo salar*) in Norway: An update for 2016. *Aquaculture Reports* 15: 100216. https://doi.org/10.1016/j.aqrep.2019.100216

Ahlm K, Hassler S, Sjölander P & Eriksson A (2010) Unnatural deaths in reindeer-herding Sami families in Sweden, 1961–2001. *International Journal of Circumpolar Health* 69: 129-137. https://doi.org/10.3402/ijch.v69i2.17432

Åhman B, Turunen M, Kumpula J, Risvoll C, Horstkotte T, Lépy É & Eilertsen SM (2022) Role of supplementary feeding in reindeer husbandry. *In*: Horstkotte T, Holand O, Kumpula J & Moen J (Eds): *Reindeer husbandry and global environmental change. Pastoralism in Fennoscandia*, pp. 232-248. Routledge, London. https://doi.org/10.4324/9781003118565-17

Ahonen H, Stafford KM, Lydersen C, de Steur L & Kovacs KM (2019) A multi-year study of narwhal occurrence in the western Fram Strait—detected via passive acoustic monitoring. *Polar Research* 38: 3468. https://doi.org/10.33265/polar.v38.3468

Akan N & Fortes AM (2015) Review: insights into molecular and metabolic events associated with fruit response to post-harvest fungal pathogens. *Frontiers in Plant Science* 6: 1-14. https://doi.org/10.3389/fpls.2015.00889

Akperov M, Rinke A, Mokhov II, Matthes H, Semenov VA, Adakudlu M, Cassano J, Christensen JH, Dembitskaya MA, Dethloff K, Fettweis X, Glisan J, Gutjahr O, Heinemann G, Koenigk T, Koldunov NV, Laprise R, Mottram R, Nikiéma O, Scinocca JF, Sein D, Sobolowski S, Winger K & Zhang W (2018) Cyclone Activity in the Arctic from an ensemble of regional climate models (Arctic CORDEX). *Journal of Geophysical Research – Atmospheres* 123: 2537-2554. https://doi.org/10.1002/2017JD027703

Akperov M, Rinke A, Mokhov II, Semenov VA, Parfenova MR, Matthes H, Adakudlu M, Boberg F, Christensen JH, Dembitskaya MA, Dethloff K, Fettweis X, Gutjahr O, Heinemann G, Koenigk T, Koldunov NV, Laprise R, Mottram R, Nikiéma O, Sein D, Sobolowski S, Winger K & Zhang W (2019) Future projections of cyclone activity in the Arctic for the 21st

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

century from regional climate models (Arctic-CORDEX). *Global and Planetary Change* 182: 103005. https://doi.org/10.1016/j.gloplacha.2019.103005

Albretsen J & Asplin L (2021) Fysisk oseanografiske forhold i produksjonsområdene for akvakultur - oppdatering september 2021. *Rapport fra havforskningen* 2021-49. Institute of Marine Research, Bergen. https://www.hi.no/hi/nettrapporter/rapport-fra-havforskningen-2021-49

Alcock I, White MP, Taylor T, Coldwell DF, Gribble MO, Evans KL, Corner A, Vardoulakis S & Fleming LE (2017) 'Green' on the ground but not in the air: Pro-environmental attitudes are related to household behaviours but not discretionary air travel. *Global Environmental Change* 42: 136-147. https://doi.org/10.1016/j.gloenvcha.2016.11.005

Allan RP *et al.* (in total 77 drafting authors and 40 contributing authors) (2021) *Summary for Policymakers*. *In*: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R & Zhou B (Eds.): *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 3−32. Cambridge University Press, Cambridge, New York. https://doi.org/10.1017/9781009157896.001

AMAP (2021) Arctic Climate Change Update 2021: Key Trends and Impacts. Summary for Policy-makers. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. 16 pp

Amdahl P (2022) *Et dødelig polart lavtrykk*. The Norwegian Meteorological Institute, Oslo. https://www.met.no/nyhetsarkiv/et-dodelig-polart-lavtrykk

Ammunét T, Bylund H & Jepsen JU (2015) Northern geometrids and climate change: from abiotic factors to trophic interactions. *In*: Björkman C & Niemelä P (Eds): *Climate Change and Insect Pests*, pp. 235-247. https://ffpdb.slu.se/4087/1/Bjorkman%20%26%20Niemela.pdf#page=235

Amthor JS (1984) The role of maintenance respiration in plant growth. *Plant, Cell & Environment* 7: 561-569.

Andersen AO (2022) Muskox multiplications: the becoming of a resource, relations and place in Kangerlussuaq, West Greenland. *Acta Borealia* 39: 75-94. https://doi.org/10.1080/08003831.2022.2060619

Andrews CJ (1996) How do plants survive ice? *Annals of Botany* 78: 529–536. https://doi.org/10.1006/anbo.1996.0157

Angert A, Biraud S, Bonfils C, Henning CC, Buermann W, Pinzon J, Tucker CJ, Fung I & Field CB (2005) Drier summers cancel out the CO_2 uptake enhancement induced by warmer springs. *Proceedings of the National Academy of the Sciences of the United States of America* 102: 10823-10827. https://doi.org/10.1073/pnas.0501647102

Anker-Nilssen T, Barrett R, Christensen-Dalsgaard S, Dehnhard N, Descamps S, Systad GHR, Moe B, Reiertsen TK, Bustnes JO, Erikstad KE, Follestad A, Hanssen SA, Langset M, Lorentsen SH, Lorentzen E & Strøm H (2021) Key-site monitoring in Norway 2020, including Svalbard and Jan Mayen. *SEAPOP Short Report* 1-2021. 15 pp. https://seapop.no/wp-content/uploads/2021/06/seapop-short-report-1-2021.pdf

Anonymous (2019) Weather news – Summer drought in Iceland. *Weather* 74: 262-263. https://doi.org/10.1002/wea.3342

Antão LH, Weigel B, Strona G, Hällfors M, Kaarlejärvi E, Dallas T, Opedal ØH, Heliölä J, Henttonen H, Huitu O, Korpimäki E, Kuussaari M, Lehikoinen A, Leinonen R, Lindén A, Merilä P, Pietiäinen H, Pöyry J, Salemaa M, Tonteri T, Vuorio K, Ovaskainen O, Saastamoinen M, Vanhatalo J, Roslin T & Laine AL (2022) Climate change reshuffles northern species within their niches. *Nature Climate Change* 12: 587–592. https://doi.org/10.1038/s41558-022-01381-x

AppEEARS Team (2022) *Application for Extracting and Exploring Analysis Ready Samples (AppEEARS). Ver. 2.69.* NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, USA. https://lpdaacsvc.cr.usgs.gov/appeears

Arctic Monitoring and Assessment Programme (2017) *Adaptation Actions for a Changing Arctic: Perspectives from the Barents Area*, xiv + 267pp. Arctic Monitoring and Assessment Programme, Oslo. https://www.amap.no/documents/download/2981/inline

Arctic Monitoring and Assessment Programme (2021) *Arctic Climate Change Update 2021: Key Trends and Impacts*. Arctic Monitoring and Assessment Programme, Tromsø. https://www.amap.no/documents/download/6759/inline

Arrigo KR, van Dijken GL, Castelao RM, Luo H, Rennermalm AK, Tedesco M, Mote TL, Oliver H & Yager PL (2017) Melting glaciers stimulate large summer phytoplankton blooms in southwest Greenland waters. *Geophysical Research Letters* 44: 6278-6285. https://doi.org/10.1002/2017GL073583

Artsdatabanken (2018). *Norsk rødliste for naturtyper 2018*. https://www.artsdatabanken.no/rodlistefornaturtyper

Artsdatabanken (2021a). *Norsk rødliste for arter 2021*. https://www.artsdatabanken.no/lister/rodlisteforarter/2021

Artsdatabanken (2021b). *Rødlista for arter 2021 – påvirkningsfaktorer*. https://artsdatabanken.no/rodlisteforarter2021/Resultater/Pavirkningsfaktorer

Ayaydın E & Akgönül S (2020) Finnish Sámi: Is tourism a preservation of indigenous culture?. *In*: Pongrácz E, Pavlov V & Hänninen N (Eds.): *Arctic Marine Sustainability*, pp. 391-409. Springer Polar Sciences, Springer, Cham. https://doi.org/10.1007/978-3-030-28404-6

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Badiola M, Basurko OC, Piedrahita R, Hundley P & Mendiola D (2018) Energy use in recirculating aquaculture systems (RAS): a review. *Aquacultural Engineering* 81: 57-70. https://doi.org/10.1016/j.aquaeng.2018.03.003

Bakkestuen V, Erikstad L & Halvorsen R (2008) Step-less models for regional environmental variation in Norway. *Journal of Biogeography* 35: 1906-1922. https://doi.org/10.1111/j.1365-2699.2008.01941.x

Bårdløkken B 2014. 10 prosent færre geitebønder på ett år. *Nationen* (newspaper). https://www.nationen.no/article/10-prosent-faerre-geitebonder-pa-ett-ar/

Bartlett CB, Garber AF, Gonen S & Benfey TJ (2022) Acute critical thermal maximum does not predict chronic incremental thermal maximum in Atlantic salmon (*Salmo salar*). *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology* 266: 111143. https://doi.org/10.1016/j.cbpa.2022.111143

Baxter EJ, Rodger HD, McAllen R & Doyle TK (2011) Gill disorders in marine-farmed salmon: investigating the role of hydrozoan jellyfish. *Aquaculture Environment Interactions* 1: 245-257. https://doi.org/10.3354/aei00024

Beck EH, Heim R & Hansen J (2004) Plant resistance to cold stress: Mechanisms and environmental signals triggering frost hardening and dehardening. *Journal of Biosciences* 29: 449–459. https://doi.org/10.1007/BF02712118

Beigaitė R, Tang H, Bryn A, Skarpaas O, Stordal F, Bjerke JW & Žliobaitė I (2022). Identifying climate thresholds for dominant natural vegetation types at the global scale using machine learning: Average climate versus extremes. Global Change Biology 28: 3557–3579. https://doi.org/10.1111/gcb.16110

Bell KL & Bliss LC (1978) Root growth in a polar semi-desert environment. *Canadian Journal of Botany* 56: 2470-2490. https://doi.org/10.1139/b78-299

Bell KL & Bliss LC (1980) Plant reproduction in a High Arctic environment. *Arctic and Alpine Research* 12: 1-10. https://doi.org/10.1080/00040851.1980.12004158

Benedicenti O, Pottinger TG, Collins C & Secombes CJ (2019) Effects of temperature on amoebic gill disease development: Does it play a role? *Journal of Fish Diseases* 42: 1241-1258. https://doi.org/10.1111/jfd.13047

Berge J, Heggland K, Lønne OJ, Cottier F, Hop H, Gabrielsen GW, Nøttestad L & Misund, O. A. (2015). First records of Atlantic mackerel (*Scomber scombrus*) from the Svalbard archipelago, Norway, with possible explanations for the extensions of its distribution. *Arctic* 68: 54-61. https://doi.org/10.14430/arctic4455

Bergheim A, Drengstig A, Ulgenes Y & Fivelstad S (2009) Production of Atlantic salmon smolts in Europe – current characteristics and future trends. *Aquacultural Engineering* 41: 46-52.

Bergqvist G, Bergström R & Edenius L (2001) Patterns of stem damage by moose (*Alces alces*) in young *Pinus sylvestris* stands in Sweden. *Scandinavian Journal of Forest Research* 16: 363-370. https://doi.org/10.1080/02827580119307

Bergqvist G, Bergström R, Wallgren M (2013) Summer browsing by moose on Scots pine. *Scandinavian Journal of Forest Research* 28: 110-116. https://doi.org/10.1080/02827581.2012.725767

Beylich AA & Sandberg O (2005) Geomorphic effects of the extreme rainfall event of 20–21 July, 2004 in the Latnjavagge catchment, northern Swedish Lapland. *Geografiska Annaler: Serie A, Physical Geography* 87: 409-419. https://doi.org/10.1111/j.0435-3676.2005.00267.x

Bieniek PA, Bhatt US, Walsh JE, Lader R, Griffith B, Roach JK & Thoman RL (2018) *Journal of Applied Meteorology and Climatology* 57: 1847-1863. https://doi.org/10.1175/JAMC-D-17-0276.1

Billings WD & Mooney HA (1968) The ecology of Arctic and alpine plants. *Biological Reviews* 43: 481-529.

Bintanja R & Andry O (2017) Towards a rain-dominated Arctic. *Nature Climate Change* 7: 263–267. https://doi.org/10.1038/nclimate3240

Bissolli P, Rösner B, Demircan M, Kennedy J, Khan V, Kokosadze N, Kutaladze N, Lakatos M, Mamen J, Megrelidze L, Pastor Saavedra MA, Rodríguez Camino E, Rodríguez Guisado E, Sensoy S, Spillane S, Trachte K & van der Schrier G (2020) *Europe and the Middle East*. *In*: Bissolli P, Ganter C, Li T, Mekonnen A & Sánchez-Lugo A (Chapter Eds.): *Regional Climates*. *In*: Blunden J & Arndt DS (Eds.): *State of the Climate in 2019*. *Bulletin of the American Meteorological Society* 101: S363-S382. https://doi.org/10.1175/2020BAMSStateoftheClimate_Chapter7.1

Bjerke JW (2011) Winter climate change: Ice encapsulation at mild subfreezing temperatures kills freeze-tolerant lichens. *Environmental and Experimental Botany* 72: 404–408. https://doi.org/10.1016/j.envexpbot.2010.05.014

Bjerke JW, Karlsen SR, Høgda KA, Malnes E, Jepsen JU, Lovibond S, Vikhamar-Schuler D & 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. *Environmental Research Letters* 9: 084006. https://doi:10.1088/1748-9326/9/8/084006

Bjerke JW, Tømmervik H, Zielke M & Jørgensen M (2015) Impacts of snow season on ground-ice accumulation, soil frost and primary productivity in a grassland of sub-Arctic Norway. *Environmental Research Letters* 10: 095007. https://doi:10.1088/1748-9326/10/9/095007

Bjerke JW, Treharne R, Vikhamar-Schuler D, Karlsen SR, Ravolainen V, Bokhorst S, Phoenix GK, Bochenek Z & Tømmervik H (2017a) Understanding the drivers of extensive plant damage in boreal and Arctic ecosystems: Insights from field surveys in the aftermath of

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

damage. *Science of the Total Environment* 599-600: 1965–1976. https://doi:10.1016/j.scitotenv.2017.05.050

Bjerke JW, Bokhorst S, Callaghan TV & Phoenix GK (2017b) Persistent reduction of segment growth and photosynthesis in a widespread and important sub-Arctic moss species after cessation of three years of experimental winter warming. *Functional Ecology* 31: 127–134. https://doi.org/10.1111/1365-2435.12703

Bjerke JW, Elverland E, Jaakola L, Lund L, Zagajewski B, Bochenek Z, Kłos A & Tømmervik H (2018a) High tolerance of a high-Arctic willow and graminoid to simulated ice encasement. *Boreal Environmental Research* 23: 329–338. http://www.borenv.net/BER/archive/ber231-6.htm

Bjerke JW, Elvebakk A & Tømmervik H (2018b) Alpine garden plants from six continents show high vulnerability to ice encasement. *Norsk Geografisk Tidsskrift–Norwegian Journal of Geography* 72: 57–64. https://doi.org/10.1080/00291951.2017.1391876

Björk RG & Molau U (2007) Ecology of alpine snowbeds and the impact of global change. *Arctic, Antarctic & Alpine Research* 39: 34–43 https://doi.org/10.1657/1523-0430(2007)39[34:EOASAT]2.0.CO;2

Björnsson H (2010) Understanding jökulhlaups: from tale to theory. *Journal of Glaciology* 56: 1002-1010. https://doi.org/10.3189/002214311796406086

Blöschl G, Kiss A, Viglione A Barriendos M, Böhm O, Brázdil R, Coeur D, Demarée G, Llasat MC, Macdonald N, Retsö D, Roald L, Schmocker-Fackel P, Amorim I, Bělínová M, Benito G, Bertolin C, Camuffo D, Cornel D, Doktor R, Elleder L, Enzi S, Garcia JC, Glaser R, Hall J, Haslinger K, Hofstätter M, Komma J, Limanówka D, Lun D, Panin A, Parajka J, Petrić H, Rodrigo FS., Rohr C, Schönbein J, Schulte L, Silva LP, Toonen WHJ, Valent P, Waser J & Wetter O (2020) Current European flood-rich period exceptional compared with past 500 years. *Nature* 583: 560–566. https://doi.org/10.1038/s41586-020-2478-3

Boertmann D & Bay C (Eds) (2018) *Grønlands Rødliste 2018 – Fortegnelse over grønlandske dyr og planters trusselstatus*. Pinngortitalerfiffik (Greenland Institute of Natural Resources), Nuuk. https://natur.gl/raadgivning/roedliste/

Bogadóttir R (2020) The social metabolism of quiet sustainability in the Faroe Islands. *Sustainability* 12: 735. https://doi.org/10.3390/su12020735

Bokhorst S, Bjerke JW, Tømmervik H, Callaghan TV & Phoenix GK (2009) Winter warming events damage sub-Arctic vegetation: consistent evidence from an experimental manipulation and a natural event. *Journal of Ecology* 97: 1408–1415. https://doi.org/10.1111/j.1365-2745.2009.01554.x

Bokhorst S, Phoenix GK, Berg MP, Callaghan TV, Kirby-Lambert C & Bjerke JW (2015) Climatic and biotic extreme events moderate long-term responses of above- and belowground

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

sub-Arctic heathland communities to climate change. *Global Change Biology* 21: 4063–4075. https://doi.org/10.1111/gcb.13007

Bokhorst S, Pedersen SH, Brucker L, Anisimov O, Bjerke JW, Brown RD, Ehrich D, Essery RLH, Heilig A, Ingvander S, Johansson C, Johansson M, Jónsdóttir IS, Niila I, Luojus K, Macelloni G, Mariash H, McLennan D, Rosqvist GN, Sato A, Savela H, Schneebeli M, Sokolov A, Sokratov SA, Terzago S, Vikhamar-Schuler D, Williamson SN, Qiu Y & Callaghan TV (2016) Changing Arctic snow cover: A review of recent developments and assessment of future needs for observations, modelling, and impacts. *Ambio* 45: 516-537. https://doi.org/10.1007/s13280-016-0770-0

Bokhorst S, Jaakola L, Karppinen K, Edvinsen GK, Mæhre HK & Bjerke JW (2018) Contrasting survival and physiological responses of sub-Arctic plant types to extreme winter warming and nitrogen. *Planta* 247: 635-648.

Borish D, Cunsolo A, Snook J, Shiwak I, Wood M, HERD Caribou Project Steering Committee, Mauro I, Dewey C & Harper SL (2021) “Caribou was the reason, and everything else happened after”: Effects of caribou declines on Inuit in Labrador, Canada. *Global Environmental Change* 68: 102268. https://doi.org/10.1016/j.gloenvcha.2021.102268

Bosch-Belmar M, Milisenda G, Basso L, Doyle TK, Leone A & Piraino S (2020) Jellyfish impacts on marine aquaculture and fisheries. *Reviews in Fisheries Science & Aquaculture* 29: 242-259. https://doi.org/10.1080/23308249.2020.1806201

Box JE, Bhatt US, Christensen TR, Derksen C, Gerland S, Granskog M, Isakesen K, Kohler J, Mård J, Meier WN, Mudryk L, Romanovsky VE, Shiklomanov A, Smith S, Vanha-Majamaa I, Wouter B & Yang D (2022) Recent development in Arcitc climate observationa indicators. *In*: AMAP Arctic Climate Change Update 2021: key trends and impacts, pp. 7-30. Arctic Monitoring and Assessment Programme, Tromsø.

Breidenbach J, Ellison D, Petersson H, Korhonen KT, Henttonen HM, Wallerman J, Fridman J, Gobakken T, Astrup R & Næsset E (2022) Harvested area did not increase abruptly − how advancements in satellite-based mapping led to erroneous conclusions. *Annals of Forest Science* 79: 2. https://doi.org/10.1186/s13595-022-01120-4

Breili K (2022) Evolution of sea-level trends along the Norwegian coast from 1960 to 2100. *Ocean Dynamics* 72: 115–136. https://doi.org/10.1007/s10236-021-01492-7

Brett JR (1969) Temperature and fish. *Chesapeake Science* 10: 275-276.

Brisson CP, Coverdale TC & Bertness MD (2014) Salt marsh die-off and recovery reveal disparity between the recovery of ecosystem structure and service provision. *Biological Conservation* 179: 1-5. https://10.1016/j.biocon.2014.08.013

Brown PJ & DeGaetano AT (2011) A paradox of cooling winter soil surface temperatures in a warming northeastern United States. *Agricultural and Forest Meteorology* 151: 947-956. https://doi.org/10.1016/j.agrformet.2011.02.014

Brown R, Vikhamar Schuler D, Bulygina O, Derksen C, Luojus K, Mudryk L, Wang L & Yang D (2017). Arctic terrestrial snow cover. *In*: *Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017*, pp. 25-64. Arctic Monitoring and Assessment Programme, Oslo. https://www.amap.no/documents/doc/snow-water-ice-and-permafrost-in-the-arctic-swipa-2017/1610

Bui TAT, Stridh H & Molin M (2021) Influence of weather conditions on the quality of 'Ingrid Marie' apples and their susceptibility to grey mould infection. *Journal of Agriculture and Food Research* 3: 100104. https://doi.org/10.1016/j.jafr.2021.100104

Buitenwerf R, Sandel B, Normand S, Mimet A & Svenning JC (2018) Land-surface greening suggests vigorous woody regrowth throughout European semi-natural vegetation. *Global Change Biology* 24: 5789-5801. https://doi.org/10.1111/gcb.14451

Bulygina ON, Groisman PY, Razuvaev VN & Radionov VF (2010) Snow cover basal ice layer changes over Northern Eurasia since 1966. *Environmental Research Letters* 5: 015004. https://doi.org/10.1088/1748-9326/5/1/015004

Burke H, Gardner I & Farrell AP (2020) *A Review of the 2019 Newfoundland and Labrador South Coast Cultured Atlantic Salmon Mortality Event*. Fisheries and Marine Institute of Memorial University of Newfoundland, St. John's. https://www.gov.nl.ca/ffa/files/publications-pdf-2019-salmon-review-final-report.pdf

Caldeira K & Wickett ME (2003) Anthropogenic carbon and ocean pH. *Nature* 425: 365-365. https://doi.org/10.1038/425365a

Callaghan TV, Björn LO, Chernov Y, Chapin T, Christensen TR, Huntley B, Ims RA, Johansson M, Jolly D, Jonasson S, Matveyeva N, Panikov N, Oechel W, Shaver G & Henttonen H (2004) Effects on the structure of arctic ecosystems in the short- and long-term perspectives. *Ambio* 33:436–447. https://doi.org/10.1579/0044-7447-33.7.436

Callaghan TV, Jonasson C, Thierfelder T, Zhenlin Y, Hedenås H, Johansson M, Molau U, Van Bogaert R, Michelsen A, Olofsson J, Gwynn-Jones D, Bokhorst S, Phoenix GK, Bjerke JW, Tømmervik H, Christensen TR, Hanna E, Koller EK & Sloan VL (2013) Ecosystem change and stability over multiple decades in the Swedish sub-Arctic: complex processes and multiple drivers. *Philosophical Transactions of the Royal Society, B, Biological Sciences* 368: 20120488. https://doi.org/10.1098/rstb.2012.0488

Cappelen J (Ed.) (2020) Weather observations from Greenland 1958-2019. *DMI Report* 20-08, 33 pp. The Danish Meteorological Institute. https://www.dmi.dk/fileadmin/user_upload/Rapporter/TR/2020/DMIRep20-08.pdf

Cappelen J (Ed.) (2021a) The Faroe Islands – DMI Historical Climate Data Collection 1873-2020. *DMI Report* 21-05, 32 pp. The Danish Meteorological Institute. https://www.dmi.dk/fileadmin/Rapporter/2021/DMIRep21-05.pdf

Cappelen J (Ed.) (2021b) Weather observations from Greenland 1958-2019. *DMI Report* 21-08, 20 pp. The Danish Meteorological Institute. https://www.dmi.dk/fileadmin/Rapporter/2021/DMIRep21-08.pdf

Carrivick JL & Tweed FS (2019) A review of glacier outburst floods in Iceland and Greenland with a megafloods perspective. *Earth-Science Reviews* 196: 102876. https://doi.org/10.1016/j.earscirev.2019.102876

Cauvy-Faunie S & Dangles O (2019) A global synthesis of biodiversity responses to glacier retreat. *Nature Ecology & Evolution* 3: 1675-1685. https://doi.org/10.1038/s41559-019-1042-8

Caviezel C, Hunziker M & Kuhn N (2017) Bequest of the Norseman—The potential for agricultural intensification and expansion in Southern Greenland under climate change. *Land* 6: 87. https://doi.org/10.3390/land6040087

Ceccherini G, Duveiller G, Grassi G, Lemoine G, Avitabile V, Pilli R & Cescatti A (2020) Abrupt increase in harvested forest area over Europe after 2015. *Nature* 583: 72-77. https://doi.org/10.1038/s41586-020-2438-y

Ceccherini G, Duveiller G, Grassi G, Lemoine G, Avitabile V, Pilli R & Cescatti A (2021) Concerns about reported harvests in European forests Reply to Wernick, I. K. et al.; Palahi, M. et al. *Nature* 592: E18-E23. https://doi.org/10.1038/s41586-021-03294-9

Cederlund G, Ljungqvist H, Markgren G & Ståhlfelt F (1980) Foods of moose and roe deer at Grimsö in central Sweden. Results of rumen content analyses. *Swedish Wildlife Research − Viltrevy* 11: 169-247.

Chamberlain CJ, Cook BI, de Cortazar-Atauri IG & Wolkovich EM (2019) Rethinking false spring risk. *Global Change Biology* 25: 2209-2220. https://doi.org/10.1111/gcb.14642

Chen C, Park T, Wang X, Piao S, Xu B, Chaturvedi RK, Fuchs R, Brovkin V, Ciais P, Fensholt R, Tømmervik H, Bala G, Zhu Z, Nemani RR & Myneni R (2019) China and India lead in greening of the world through land-use management. *Nature Sustainability* 2: 122–129. https://doi.org/10.1038/s41893-019-0220-7

Chen D, Zhang P, Seftigen K, Ou T, Giese M & Barthel R (2020) Hydroclimate changes over Sweden in the twentieth and twenty-first centuries: a millennium perspective. *Geografiska Annaler: Series A, Physical Geography* 103: 103-131. https://doi.org/10.1080/04353676.2020.1841410

Chen L, Aalto J & Luoto M (2021) Significant shallow-depth soil warming over Russia during the past 40 years. *Global and Planetary Change* 197: 103394. https://doi.org/10.1016/j.gloplacha.2020.103394

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Cho MH, Yang AR, Baek EH, Kang SM, Jeong SJ, Kim JY & Kim BM (2018) Vegetation-cloud feedbacks to future vegetation changes in the Arctic regions. *Climate Dynamics* 50: 3745–3755. https://doi.org/10.1007/s00382-017-3840-5

Cohen J, Ye H & Jones J (2015) Trends and variability in rain-on-snow events. *Geophysical Research Letters* 42: 7115-7122. https://doi.org/10.1002/2015GL065320

Coleman MA & Wernberg T (2020) The silver lining of extreme events. *Trends in Ecology & Evolution* 35: 1065-1067. https://doi.org/10.1016/j.tree.2020.08.013

Collins M, Knutti R, Arblaster J, Dufresne JL, Fichefet T, Friedlingstein P, Gao X, Gutowski WJ, Johns T, Krinner G, Shongwe M, Tebaldi C, Weaver AJ & Wehner M (2013) Long-term climate change: projections, commitments and irreversibility. *In*: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V & Midgley PM (Eds), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, New York.

Collins M, Sutherland M, Bouwer L, Cheong S-M, Frölicher T, Jacot Des Combes H, Koll Roxy M, Losada I, McInnes K, Ratter B, Rivera-Arriaga E, Susanto RD, Swingedouw D & Tibig L (2019) Extremes, abrupt changes and managing risk. *In*: Pörtner H-O, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Alegría A, Nicolai M, Okem A, Petzold J, Rama B, Weyer NM (eds.): *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Cambridge University Press, Cambridge, UK & New York, NY, USA, pp. 589-655. https://doi.org/10.1017/9781009157964.008

Coppola E, Raffaele F, Giorgi F, Graziano G, Xuejie G, Ciarlo JM, Sines TR, Torres-Alavez JA, Das S, di Sante F, Pichelli E, Glazer R, Müller SK, Omar SA, Ashfaq M, Bukovsky M, Im ES, Jacob D, Teichmann C, Remedio A, Remke T, Kriegsmann A, Bülow K, Weber T, Buntemeyer L, Sieck K & Rechi D (2021) Climate hazard indices projections based on CORDEX-CORE, CMIP5 and CMIP6 ensemble. *Climate Dynamics* 57: 1293–1383. https://doi.org/10.1007/s00382-021-05640-z

Coulson SJ, Leinaas HP, Ims RA & Søvik G (2000) Experimental manipulation of the winter surface ice layer: the effects on a high arctic soil microarthropod community. *Ecography* 23: 299–306. https://doi.org/10.1034/j.1600-0587.2000.d01-1638.x

Cramer VA, Hobbs RJ & Standish RJ (2008) What's new about old fields? Land abandonment and ecosystem assembly. *Trends in Ecology & Evolution* 23: 104-112. https://doi.org/10.1016/j.tree.2007.10.005

Crawford AD, Lukovich JV, McCrystall MR, Stroeve JC & Barber DG (2022) Reduced sea ice enhances intensification of winter storms over the Arctic Ocean. *Journal of Climate* 35: 3353-3370. https://doi.org/10.1175/JCLI-D-21-0747.1

Crawford RMM (1992) Oxygen availability as an ecological limit to plant distribution. *Advances in Ecological Research* 23: 93–185. https://doi.org/10.1016/S0065-2504(08)60147-6

Crawford RMM (2000) Ecological hazards of oceanic environments. *New Phytologist* 147: 257-281.

Crawford RMM, Chapman HM & Hodge H (1994) Anoxia tolerance in high arctic vegetation. *Arctic and Alpine Research* 26: 308–312. https://doi.org/10.2307/1551944

Crawford RMM & Palin MA (1981) Root respiration and temperature limits to the north-south distribution of four perennial maritime plants. *Flora* 171: 338-354.

Csapó HK, Grabowski M, Węsławski JM (2021) Coming home - boreal ecosystem claims Atlantic sector of the Arctic. *Science of The Total Environment* 771: 144817. https://doi.org/10.1016/j.scitotenv.2020.144817

Cuyler C, Rowell J, Adamczewski J, Anderson M, Blake J, Bretten T, Brodeur V, Campbell M, Checkley SL, Cluff HD, Côté SD, Davison T, Dumond M, Ford B, Gruzdev A, Gunn A, Jones P, Kutz S, Leclerc LM, Mallory C, Mavrot F, Mosbacher JB, Okhlopkov IM, Reynolds P, Schmidt NM, Sipko T, Suitor M, Tomaselli M & Ytrehus B (2020) Muskox status, recent variation, and uncertain future. *Ambio* 49: 805–819. https://doi.org/10.1007/s13280-019-01205-x

Dahlke HE, Lyon SW, Stedinger JR, Rosqvist G & Jansson P (2012) Contrasting trends in floods for two sub-arctic catchments in northern Sweden – does glacier presence matter? *Hydrology and Earth System Sciences* 16: 2123-2141. https://doi.org/10.5194/hess-16-2123-2012

DeGaetano AT, Cameron MD & Wilks DS (2001) Physical simulation of maximum seasonal soil freezing depth in the United States using routine weather observations. *Journal of Applied Meteorology* 40: 546-555. https://doi.org/10.1175/1520-0450(2001)040<0546:PSOMSS>2.0.CO;2

Davini P, Cagnazzo C, Neale R & Tribbia J (2012) Coupling between Greenland blocking and the North Atlantic Oscillation pattern, *Geophysical Research Letters* 39: L14701. https://doi.org/10.1029/2012GL052315

Davini P, Weisheimer A, Balmaseda M, Johnson SJ, Molteni F, Roberts CD, Senan R & Stockdale TN (2021) The representation of winter Northern Hemisphere atmospheric blocking in ECMWF seasonal prediction systems. *Quarterly Journal of the Royal Meteorological Society* 147: 1344–1363. https://doi.org/10.1002/qj.3974

Demiroglu OC, Lundmark L, Saarinen J & Müller DK (2019) The last resort? Ski tourism and climate change in Arctic Sweden. *Journal of Tourism Futures* 6: 91-101. https://doi.org/10.1108/JTF-05-2019-0046

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

De Pelsmaeker N, Korslund L & Steifetten Ø (2020) High-elevational occurrence of two tick species, *Ixodes ricinus* and *I. trianguliceps*, at their northern distribution range. *Parasites & Vectors* 14: 161. https://doi.org/10.1186/s13071-021-04604-w

Derocher A, Wiig Ø & Bangjord G (2000) Predation of Svalbard reindeer by polar bears. *Polar Biology* 23: 675–678. https://doi.org/10.1007/s003000000138

Didan K (2015) *MOD13A3 MODIS/Terra vegetation Indices Monthly L3 Global 1km SIN Grid V006* [Data set]. NASA EOSDIS Land Processes DAAC. https://doi.org/10.5067/MODIS/MOD13A3.006

DNV GL (2019) *Sustainable Blue Economy in the Norwegian Arctic*. Centre for the Ocean and the Arctic, Tromsø, 103 pp. https://www.havarktis.no/img/Sustainable-Blue-Economy-in-the-Norwegian-Arctic-Part-1-Status_FINAL.pdf

Doyle S, Cabot D, Walsh A, Inger R, Bearhop S & McMahon BJ (2020) Temperature and precipitation at migratory grounds influence demographic trends of an Arctic-breeding bird. *Global Change Biology* 26: 5447-5458. https://doi.org/10.1111/gcb.15267

Doyle S, Cabot D, Griffin L, Kane A, Colhoun K, Bearhop S & McMahon BJ (2021) Spring and autumn movements of an Arctic bird in relation to temperature and primary production. *Journal of Avian Biology* 52: 02830. https://doi.org/10.1111/jav.02830

Drinkwater KF (2006) The regime shift of the 1920s and 1030s in the North Atlantic. *Progress in Oceanography* 68: 134-151. https://doi.org/10.1016/j.pocean.2006.02.011

Druckenmiller ML, Moon T & Thoman R (chapter eds.) (2021) The Arctic. *In*: State of the Climate in 2020 (Eds. Blunden J & Boyer T). *Bulletin of the American Meteorological Society* 102 (8): S263-S308. https://doi.org/10.1175/BAMS-D-21-0086.1

Dunn RJH, Aldred F, Gobron N, Miller JB & Willett KM (chapter eds.) (2022) Global climate. *In*: State of the Climate in 2021 (Eds. Blunden J & Boyer T). *Bulletin of the American Meteorological Society* 103 (8): S11-S142. https://doi.org/10.1175/BAMS-D-22-0092.1

Dyrrdal AV, Isaksen K, Jacobsen JKS & Nilsen IB (2020) Present and future changes in winter climate indices relevant for access disruptions in Troms, northern Norway. *Natural Hazards and Earth System Sciences* 20: 1847–1865. https://doi.org/10.5194/nhess-20-1847-2020

Eckdahl JA, Kristensen JA & Metcalfe DB (2022) Climatic variation drives loss and restructuring of carbon and nitrogen in boreal forest wildfire. *Biogeosciences* 19: 2487-2506. https://doi.org/10.5194/bg-19-2487-2022

Eide NE, Stokke B & Framstad E (2020) Fjell. *In*: Jakobsson S & Pedersen B (Eds): Naturindeks for Norge 2020. *NINA Rapport* 1886, pp. 60-67. Norwegian Institute for Nature Research, Trondheim. https://brage.nina.no/nina-xmlui/bitstream/handle/11250/2686068/ninarapport1886.pdf?sequence=3&isAllowed=y

Eide W, Ahrné K, Bjelke U, Nordström S, Ottosson E, Sandström J & Sundberg S (Eds) (2020). *Rödlistader arter i Sverige 2020*. SLU Artdatabanken, Uppsala. https://www.artdatabanken.se/var-verksamhet/rodlistning/

Eilu P, Bjerkgård T, Franzson H, Gautneb H, Häkkinen T, Jonsson E, Keiding JK, Pokki J, Raaness A, Reginiussen H, Róbertsdóttir BG, Rosa D, Sadeghi M, Sandstad JS, Stendal H, Þórhallsson ER & TörmänenT (2021). *The Nordic supply potential of critical metals and minerals for a Green Energy Transition*. *Nordic Innovation Report*, 94 pp. Nordic Innovation & Nordic Council of Ministers, Oslo. http://urn.kb.se/resolve?urn=urn:nbn:se:norden:org:diva-12199

Einarsson MÁ (1984) Climate of Iceland. In: *World Survey of Climatology* Vol. 15, pp. 673–697, Ed.: Loon H. Elsevier, Amsterdam, New York.

Eira AJ, Granefjell SO, Eira IH & Tuorda ER (2020) *Analyse av virkningene for reindriftene ved planlagt gruvedrift i Nussir og Ulvreyggen i Kvalsund kommune. Del 1. Ingrepskartlegging og reindriftsfaglig vurdering*. Stiftelsen Protect Sápmi, Tromsø, 219 pp.

Eira IMG, Oskal A, Hanssen-Bauer I & Mathiesen SD (2018). Snow cover and the loss of traditional indigenous knowledge. *Nature Climate Change* 8: 928–931. https://doi.org/10.1038/s41558-018-0319-2

Eliasen K (2013) *Sandeel, Ammodytes spp., as a link between climate and higher trophic levels on the Faroe shelf*. PhD thesis, 31 pp. Aarhus University. http://81.25.190.152/PDF/Ritgerdir/2013/PhD_thesis_sandeel.pdf

Eldegard K, Syvertsen PO, Bjørge A, Kovacs K, Støen OG & van der Kooij J (2021a) *Pattedyr: Vurdering av ringsel* Pusa hispida *for Norge*. Rødlista for arter 2021. Artsdatabanken. https://www.artsdatabanken.no/lister/rodlisteforarter/2021/11063

Eldegard K, Syvertsen PO, Bjørge A, Kovacs K, Støen OG & van der Kooij J (2021b) *Pattedyr: Vurdering av grønlandshval* Balaena mysticetus *for Norge*. Rødlista for arter 2021. Artsdatabanken. https://www.artsdatabanken.no/lister/rodlisteforarter/2021/3990

Eldegard K, Syvertsen PO, Bjørge A, Kovacs K, Støen OG & van der Kooij J (2021c) *Pattedyr: Vurdering av narhval* Monodon monoceros *for Norge*. Rødlista for arter 2021. Artsdatabanken. https://www.artsdatabanken.no/lister/rodlisteforarter/2021/20522

Eldegard K, Syvertsen PO, Bjørge A, Kovacs K, Støen OG & van der Kooij J (2021d) *Pattedyr: Vurdering av steinkobbe* Phoca vitulina *for Svalbard*. Rødlista for arter 2021. Artsdatabanken. https://www.artsdatabanken.no/lister/rodlisteforarter/2021/4135

Eldegard K, Syvertsen PO, Bjørge A, Kovacs K, Støen OG & van der Kooij J (2021e) *Pattedyr: Vurdering av rein* Rangifer tarandus *for Svalbard*. Rødlista for arter 2021. Artsdatabanken. https://www.artsdatabanken.no/lister/rodlisteforarter/2021/19053

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Eliasen K, Reinert J, Gaard E, Hansen B, Jacobsen JA, Grønkjær P & Christensen JT (2011) Sandeel as a link between primary production and higher trophic levels on the Faroe shelf. *Marine Ecology Progress Series* 438: 185-194. https://doi.org/10.3354/meps09301

Emblemsvåg M, Werner KM, Núñez-Riboni I, Frelat R, Christensen HT, Fock HO, Primicerio R (2022) Deep demersal fish communities respond rapidly to warming in a frontal region between Arctic and Atlantic waters. *Global Change Biology* 28: 2979-2990. https://doi.org/10.1111/gcb.16113

Eskildsen DP, Vikstrøm T, Jørgensen MF & Moshøj CM (2020) Overvågning af de almindelige fuglearter i Danmark 1975-2019. Årsrapport for Punkttællingsprogrammet. Dansk Ornitologisk Forening, Copenhagen. https://www.dof.dk/images/nyheder/dokumenter/Overvagning_af_de_almindelige_fuglearter_i_Danmark_1975-2019.pdf

Estilow TW, Young AH & Robinson DA (2015) A long-term Northern Hemisphere snow cover extent data record for climate studies and monitoring. *Earth System Science Data* 7: 137-142. https://doi.org/10.5194/essd-7-137-2015

European Academies Science Advisory Council (2013) Trends in extreme weather events in Europe: implications for national and European Union adaptation strategies. *EASAC policy report* 22, 19 pp. EASAC Secretariat, Halle.

European Environment Agency (2004) *Impacts of Europe's Changing Climate: an Indicator-based Assessment.* European Environment Agency, Copenhagen.

European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Blengini GA, Latunussa CEL, Eynard U, Torres de Matos C, Wittmer D, Georgitzikis K, Pavel C, Carrara S, Mancini L, Unguru M, Blagoeva D, Mathieux F & Pennington D (2020). *Study on the EU's list of Critical Raw Materials, Final Report*. 152 pp. Publications Office, EU. https://doi.org/10.2873/11619

Eythorsson D, Garðdarsson SM, Ahmad SK, Hossain F & Nijssen B (2019) Arctic climate and snow cover trends – Comparing Global Circulation Models with remote sensing observations. *International Journal of Applied Earth Observation and Geoinformation* 80: 71-81. https://doi.org/10.1016/j.jag.2019.04.003

Falconer L, Hjøllo SS, Telfer TC, McAdam BJ, Hermansen Ø & Ytteborg E (2020) The importance of calibrating climate change projections to local conditions at aquaculture sites. *Aquaculture* 514: 734487. https://doi.org/10.1016/j.aquaculture.2019.734487

Fauchald P, Anker-Nilssen T, Barret RT, Bustnes JO, Bårdsen BJ, Christensen-Dalsgaard S, Descamps S, Engen S, Erikstad KE, Hanssen SA, Lorentsen SH, Moe B, Reiertsen TK, Strøm H & Systad GH (2015). The status and trends of seabirds breeding in Norway and Svalbard. *NINA Rapport* 1151. 84 pp. Norwegian Institute for Nature Research, Trondheim. https://hdl.handle.net/10037/7625

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Favero P (2000) "O' Sole Mio": Italian charter tourists' experiences of the midnight sun in North Cape, Norway. *Anthropological Quarterly* 73: 1-19. https://www.jstor.org/stable/3317471

Finnish Meteorological Institute (2022) Temperature and precipitation statistics from 1961 onwards. https://en.ilmatieteenlaitos.fi/statistics-from-1961-onwards

Fisheries Management of Scotland (2020) *Fish Farming – North Carradale Escape*. Fisheries Management of Scotland, Edinburgh. https://fms.scot/fish-farming/north-carradale-escape/

Foley J, Kutzbach J, Coe M, Coe MT & Levis S (1994) Feedbacks between climate and boreal forests during the Holocene epoch. *Nature* 371: 52–54. https://doi.org/10.1038/371052a0

Foucher A, Evrard O, Chabert C, Cerdan O, Lefevre I, Vandromme R & Salvador-Blanes S (2019) Erosional response to land abandonment in rural areas of Western Europe during the Anthropocene: A case study in the Massif-Central, France. *Agriculture, Ecosystems & Environment* 284: 106582. https://doi.org/10.1016/j.agee.2019.106582

Ford JD, Pearce T, Canosa IV & Harper S (2021) The rapidly changing Arctic and its societal implications. *Wiley Interdisciplinary Reviews* 12: e735. https://doi.org/10.1002/wcc.735

Ford VL & Frauenfeld OW (2022) Arctic precipitation recycling and hydrologic budget changes in response to sea ice loss. *Global and Planetary Change* 209: 103752. https://doi.org/10.1016/j.gloplacha.2022.103752

Forkel M, Drüke M, Thurner M, Dorigo W, Schaphoff S, Thonicke K, von Bloh W & Carvalhais N (2019) Constraining modelled global vegetation dynamics and carbon turnover using multiple satellite observations. *Scientific Reports* 9: 18757. https://doi.org/10.1038/s41598-019-55187-7

Førland EJ, Benestad RE, Flatøy F, Hanssen-Bauer I, Haugen JE, Isaksen K, Sorteberg A & Ådlandsvik B (2009) Climate development in north Norway and the Svalbard region during 1900–2100. *Norwegian Polar Institute Report Series* 128: 1-43.

Formetta G, Kam J, Sadeghi S, Tootle G & Piechota T (2021) Atlantic Ocean variability and European Alps winter precipitation. *Water* 13: 3377. https://doi.org/10.3390/w13233377

Frainer A, Primicerio R, Kortsch S, Aune M, Dolgov AV, Fossheim M & Aschan MM (2017) Climate-driven changes in functional biogeography of Arctic marine fish communities. *Proceedings of the National Academy of Sciences* 114: 12202-12207. https://10.1073/pnas.1706080114

Framstad E (Ed) (2014) Terrestrisk naturovervåking i 2013: Markvegetasjon, epifytter, smågnagere og fugl. Sammenfatning av resultater. *NINA Rapport* 1036. 158 pp. Norwegian Institute for Nature Research, Trondheim. https://naturindeks.nina.no/docs/6685a4ab-aba6-40c9-91fa-8b5e18412648.pdf

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Fremstad E (1997) Vegetasjonstyper for Norge. *NINA Temahefte* 12. 279 pp. Norwegian Institute for Nature Research, Trondheim.

Froehlich HE, Gentry RR & Halpern BS (2018) Global change in marine aquaculture production potential under climate change. *Nature Ecology & Evolution* 2: 1745-1750. https://doi.org/10.1038/s41559-018-0669-1

Frölicher TL, Fischer EM & Gruber N (2018) Marine heatwaves under global warming. *Nature* 560: 360-364. https://doi.org/10.1038/s41586-018-0383-9

Frost GV, Bhatt US, Epstein HE, Myers-Smith I, Phoenix GK, Berner LT, Bjerke JW, Forbes BC, Macander MC, Goetz SJ, Kerby JT, Park T, Raynolds MK, Tømmervik H & Walker DA (2020) Tundra greenness. *In*: Thoman RL, Richter-Menge . & Druckenmiller ML (Eds.): *Arctic Report Card 2020*, pp. 68-78. National Oceanic and Atmospheric Administration, Silver Spring. doi: https://doi.org/10.25923/46rm-0w23

Frost GV, Macander MC, Bhatt US, Berner LT, Bjerke JW, Epstein HE, Forbes BC, Goetz SJ, Lara MJ, Park T, Phoenix GK, Serbin SP, Tømmervik H, Walker DA & Yang D (2021) Tundra greenness. *In*: Moon TA, Druckenmiller ML & Thoman RL (Eds): *Arctic Report Card 2021*, pp. 58-65. National Oceanic and Atmospheric Administration, Silver Spring. https://doi.org/1025923/8n78-wp73

Fryday AM & Dillman KL (2022) A preliminary investigation of the lichen biota associated with recently deglaciated terrain in southeastern Alaska. *Botany* 100: 313-328. https://10.1139/cjb-2021-0087

Garcés-Pastor S, Coissac E, Lavergne S, Schwoerer C, Theurillat JP, Heintzman P, Wangensteen O, TinnerW, Rey F, Heer M, Rutzer A, Walsh K, Lammers Y, Brown A, Goslar T, Heiri O & Alsos I (2021) *High resolution ancient sedimentary DNA shows that alpine plant biodiversity is a result of human land use*. Research Square. https://assets.researchsquare.com/files/rs-908129/v1/465bb65c-346c-4f48-adbf-5932089fe342.pdf?c=1636369279

Gauslaa Y & Odasz AM (1990) Water relations, temperatures, and mineral nutrients in *Pedicularis dasyantha* (Scrophulariaceae) from Svalbard, Norway. *Ecography* 13: 112-121. https://doi.org/10.1111/j.1600-0587.1990.tb00596.x

Gilg O, Sittler B & Hanski I (2009) Climate change and cyclic predator-prey population dynamics in the high Arctic. *Global Change Biology* 15: 2634-2652. https://doi.org/10.1111/j.1365-2486.2009.01927.x

Glibert PM (2020) Harmful algae at the complex nexus of eutrophication and climate change. *Harmful Algae* 91: 101583. https://doi.org/10.1016/j.hal.2019.03.001

Glotov VE, Chlachula J, Glotova LP & Little E (2018) Causes and environmental impact of the gold-tailings dam failure at Karamken, the Russia far East. *Engineering Geology* 245: 236-247. https://doi.org/10.1016/j.enggeo.2018.08.012

Glover KA, Wennevik V, Hindar K, Skaala Ø, Fiske P, Solberg MF, Diserud OH, Svåsand T, Karlsson S, Andersen LB & Grefsrud ES (2020) The future looks like the past: Introgression of domesticated Atlantic salmon escapees in a risk assessment framework. *Fish and Fisheries* 21: 1077-1091. https://doi.org/10.1111/faf.12478

Gonzalez Antivilo F, Paz RC, Tognetti J, Keller M, Cavagnaro M, Barrio EE & Juñent FR (2020) Winter injury to grapevine secondary phloem and cambium impairs budbreak, cambium activity, and yield formation. *Journal of Plant Growth Regulation* 39: 1095–1106. https://doi.org/10.1007/s00344-019-10051-w

González-Pola C, Larsen KMH, Fratantoni P & Beszczynska-Möller A (Eds) (2020) *Report on Ocean Climate 2019*. ICES Cooperative Research Reports 350. 136 pp. https://doi.org/10.17895/ices.pub.7537

Good C & Davidson J (2016) A review of factors influencing maturation of Atlantic salmon, *Salmo salar*, with focus on water recirculation aquaculture system environments. *Journal of the World Aquaculture Society* 47: 605-632. https://doi.org/10.1111/jwas.12342

Gössling S & Dolnicar S (2022) A review of air travel behavior and climate change. *WIREs Climate Change*, early view. https://doi.org/10.1002/wcc.802

Goytia S (2021) Issues of Natural Resources Law for adopting catchment-based measures for flood risk management in Sweden. *Sustainability* 13: 2072. https://doi.org/10.3390/su13042072

Green M, Haas F & Lindström Å. (2020) *Övervakning av fåglarnas populationsutveckling. Årsrapport för 2019*. Rapport, Biologiska institutionen, Lunds Universitet, Lund.

Grefsrud ES, Karlsen Ø, Kvamme BO, Glover KA, Husa V, Hansen PK, Grøsvik BE, Samuelsen O, Sandlund N, Stien LH & Svåsand T (2021) Risikorapport norsk fiskeoppdrett 2021. *Rapport fra havforskningen* 2021-8. Institute of Marine Research, Bergen. https://www.hi.no/hi/nettrapporter/rapport-fra-havforskningen-2021-8

Gruber N, Clement D, Carter BR, Feely RA, van Heuven S, Hoppema M, Ishii M, Key RM, Kozyr A, Lauvset SK, Monaco CL, Mathis JT, Murata A, Olsen A, Perez FF, Sabine CL, Tanhua T & Wanninkhof R (2019) The oceanic sink for anthropogenic CO_2 from 1994 to 2007. *Science* 363: 1193-1199. https://doi.org/10.1126/science.aau5153

Gundersen H, Bekkby T, Norderhaug KM, Oug E, Rinde E & Fredriksen F (2018) Sukkertareskog i Nordsjøen og Skagerrak, Marint gruntvann. *Norsk rødliste for naturtyper 2018*. Artsdatabanken, Trondheim. https://artsdatabanken.no/RLN2018/342

Gunnarsson A, Garðdarsson SM & Sveinsson ÓGB (2019) Icelandic snow cover characteristics derived from a gap-filled MODIS daily snow cover product. *Hydrology and Earth System Sciences* 23: 3021-3036. https://doi.org/10.5194/hess-23-3021-2019

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Hall CM & Saarinen J (2020) 20 years of Nordic climate change crisis and tourism research: A review and future research agenda. *Scandinavian Journal of Hospitality and Tourism* 21: 102-110. https://doi.org/10.1080/15022250.2020.1823248

Hallegraeff GM, Anderson DM, Belin C, Bottein MYD, Bresnan E, Chinain M, Enevoldsen H, Iwataki M, Karlson B, McKenzie CH, Sunesen I, Pitcher GC, Provoost P, Richardson A, Schweibold L, Tester PA, Trainer VL, Yñiguez AT & Zingone A (2021) Perceived global increase in algal blooms is attributable to intensified monitoring and emerging bloom impacts. *Communications Earth & Environment* 2: 1-10. https://doi.org/10.1038/s43247-021-00178-8

Hallikainen V, Hypponen M, Pernu L & Puoskari J (2010) Family forest owners' opinions about forest management in northern Finland. *Silva Fennica* 44: 363-384. https://doi.org/10.14214/sf.158

Halsband C, Majaneva S, Hosia A, Emaus PA, Gaardsted F, Zhou Q, Nøst OA & Renaud PE (2018) Jellyfish summer distribution, diversity and impact on fish farms in a Nordic fjord. *Marine Ecology Progress Series* 591: 267-279. https://doi.org/10.3354/meps12274

Hamilton L, Lyster P & Otterstad O (2000) Social change, ecology and climate in 20th-Century Greenland. *Climatic Change* 47: 193–211. https://doi.org/10.1023/A:1005607426021

Hammond WM, Yu K, Wilson LA, Will RE, Anderegg WR, & Adams HD (2019) Dead or dying? Quantifying the point of no return from hydraulic failure in drought-induced tree mortality. *New Phytologist* 223: 1834–1843. https://doi.org/10.1111/nph.15922

Hamre LA, Bui S, Oppedal F, Skern-Mauritzen R & Dalvin S (2019) Development of the salmon louse *Lepeophtheirus salmonis* parasitic stages in temperatures ranging from 3 to 24 C. *Aquaculture Environment Interactions* 11: 429-443. https://doi.org/10.3354/aei00320

Hancock H, Hendrikx J, Eckerstorfer M & Wickström S (2021) Synoptic control on snow avalanche activity in central Spitsbergen. *The Cryosphere*: 3813-3837. https://doi.org/10.5194/tc-15-3813-2021

Handeland SO, Imsland AK, & Stefansson SO (2008) The effect of temperature and fish size on growth, feed intake, food conversion efficiency and stomach evacuation rate of Atlantic salmon post-smolts. *Aquaculture* 283: 36-42.

Hanna, E, Cappelen J, Fettweis X, Mernild SH, Mote TL, Mottram R, Steffen K, Ballinger TJ & Hall R (2021) Greenland surface air temperature changes from 1981 to 2019 and implications for ice-sheet melt and mass-balance change. *International Journal of Climatology* 41: E1336-E1352. https://doi.org/10.1002/joc.6771

Hannon GE, Halsall K, Molinari C, Stoll E, Lilley D & Bradshaw RHW (2020) Vegetation dynamics and Fire History in Färnebofjärden National Park, Central Sweden. *The Holocene* 31: 28-37. https://doi.org/10.1177/0959683620961513

Hansen BB, Isaksen K, Benestad RE, Kohler J, Pedersen ÅØ, Loe LE, Coulson SJ, Larsen LO & Varpe Ø (2014) Warmer and wetter winters: Characteristics and implications of an

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

extreme weather event in the high Arctic. *Environmental Research Letters* 9: 114021. https://doi.org/10.1088/1748-9326/9/11/114021

Hansen K (1966) Vascular plants in the Faeroes. Horizontal and vertical distribution. *Dansk Botanisk Arkiv* 24: 1-141.

Hansen ES, Sandvik H, Erikstad KE, Yoccoz NG, Anker-Nilssen T, Bader J, Descamps S, Hodges K, Mesquita MdS, Reiertsen TK & Varpe, Ø. (2021). Centennial relationships between ocean temperature and Atlantic puffin production reveal shifting decennial trends. *Global Change Biology* 27: 3753-3764. https://doi.org/10.1111/gcb.15665

Hanssen-Bauer I, Solås MK & Steffensen E (1990) The Climate of Spitsbergen. *DNMI Klima* 39/90: 1-40.

Hanssen-Bauer I, Førland EJ, Haugen JE & Tveito OE (2003) Temperature and precipitation scenarios for Norway: comparison of results from dynamical and empirical downscaling. *Climate Research* 25: 15-27. https://doi.org/10.3354/cr025015

Hanssen-Bauer I, Førland EJ, Haddeland I, Hisdal H, Mayer S, Nesje A, Nilsen JEØ, Sandven S, Sandø AB, Sorteberg A & Ådlandsvik B (Eds) (2015). Klima i Norge 2100. Kunnskapsgrunnlag for klimatilpasning oppdatert i 2015. *NCCS Report* 2/2015, 2nd edition. https://klimaservicesenter.no/kss/rapporter/kin2100

Hanssen-Bauer I, Førland EJ, Hisdal H, Mayer S, Sandø AB & Sorteberg A (Eds) (2019) Climate in Svalbard 2100 - – a knowledge base for climate adaptation. *NCCS report* 1/2019, 208 pp. https://klimaservicesenter.no/kss/rapporter/klima-pa-svalbard-2100

Härkönen L, Härkönen S, Kaitala A, Kaunisto S, Kortet R, Laaksonen S & Ylönen H (2010) Predicting range expansion of an ectoparasite – the effect of spring and summer temperatures on deer ked *Lipoptena cervi* (Diptera: Hippoboscidae) performance along a latitudinal gradient. *Ecography* 33: 906–912. https://10.1111/j.1600-0587.2009.05890.x

Harley CDG & Paine RT (2009) Contingencies and compounded rare perturbations dictate sudden distributional shifts during periods of gradual climate change. *Proceedings of the National Academy of Sciences of the United States of America* 106 (27): 11172-11176. https://doi.org/10.1073/pnas.0904946106

Harr L, Esper J, Kirchhefer JA, Zhou W & Hartl C (2021) Growth response of *Betula pubescens* Ehrh. to varying disturbance factors in northern Norway, *Trees – Structure and Function* 35: 421-431. https://doi.org/10.1007/s00468-020-02043-1

Hastrup K, Mosbech A & Grønnow B (2018) Introducing the North Water: Histories of exploration, ice dynamics, living resources, and human settlement in the Thule Region. *Ambio* 47: 162–174. https://doi.org/10.1007/s13280-018-1030-2

Heimtun B, Jóhannesson GÞ & Tuulentie S (Eds) (2015) Northern lights tourism in Iceland, Norway and Finland. *Septentrio Reports* 1-2105, 31 pp. UiT – The Arctic University of Norway, Tromsø. https://doi.org/10.7557/7.3266

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Heldbjerg H, Clausen KK, Balsby TJS, Clausen P, Nielsen RD, Skov F, Nyegaard T & Madsen J (2022) Barnacle goose *Branta leucopsis* derogation shooting effort in relation to abundance and vulnerable crops. *Agriculture, Ecosystems & Environment* 325: 1873-2305. https://10.1016/j.agee.2021.107746

Henriques I & Böhm S (2022) The perils of ecologically unequal exchange: contesting rare-earth mining in Greenland. *Journal of Cleaner Production* 349: 131378. https://doi.org/10.1016/j.jclepro.2022.131378

Hertzberg K & Leinaas H (1998) Drought stress as a mortality factor in two pairs of sympatric species of *Collembola* at Spitsbergen, Svalbard. *Polar Biology* 19: 302–306. https://doi.org/10.1007/s003000050250

Hevrøy EM, Waagbø R, Torstensen BE, Takle H, Stubhaug I, Jørgensen SM, Torgersen T, Tvennin L, Susort S, Breck O & Hansen T (2012) Ghrelin is involved in voluntary anorexia in Atlantic salmon raised at elevated sea temperatures. *General and comparative endocrinology* 175: 118-134. https://doi.org/10.1016/j.ygcen.2011.10.007

Hickler T, Vohland K, Feehan J, Miller PA, Smith B, Costa L, Giesecke T, Fronzek S, Carter TR, Cramer W, Kühn I & Sykes MT (2012) Projecting the future distribution of European potential natural vegetation zones with a generalized, tree species-based dynamic vegetation model. *Global Ecology and Biogeography* 21: 50-63. https://doi.org/10.1111/j.1466-8238.2010.00613.x

Hinojosa L, Napoléone C, Moulery M & Lambin EF (2016) The "mountain effect" in the abandonment of grasslands: Insights from the French Southern Alps. *Agriculture, Ecosystems & Environment* 221: 115-124. https://doi.org/10.1016/j.agee.2016.01.032

Hjort J, Karjalainen O, Aalto J, Westermann S, Romanovsky VE, Nelson FE, Etzelmüller B & Luoto M (2018) Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nature Communications* 9: 5147. https://10.1038/s41467-018-07557-4

Hjort J, Streletskiy D, Dore G, Wu Q, Bjella K & Luoto M (2022) Impacts of permafrost degradation on infrastructure. *Nature Reviews Earth & Environment* 3: 24-38. https://doi.org/10.1038/s43017-021-00247-8

Hlásny T, König L, Krokene P, Lindner M, Montagné-Huck C, Müller J, Qin H, Raffa K, Schelhaas MJ, Svoboda M, Viiri H & Seidl R (2021) Bark beetle outbreaks in Europe: State of knowledge and ways forward for management. *Current Forestry Reports* 7: 138–165. https://doi.org/10.1007/s40725-021-00142-x

Hock R Rasul G, Adler C, Cáceres B, Gruber S, Hirabayashi Y, Jackson M, Kääb A, Kang S, Kutuzov S, Milner A, Molau U, Morin S, Orlove B & Steltzer H (2019) High Mountain Areas. *In*: Pörtner HO, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Alegría A, Nicolai M, Okem A, Petzold J, Rama B & Weyer NM (eds.): *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Cambridge University

Press, Cambridge, UK & New York, NY, USA, pp. 131-202. https://doi.org/10.1017/9781009157964.004

Hofgaard A, Tømmervik H, Rees G & Hanssen F (2013) Latitudinal forest advance in northernmost Norway since the early 20th century. *Journal of Biogeography* 40: 938–949. https://doi.org/10.1111/jbi.12053

Høgda KA, Tømmervik H & Karlsen SR (2013) Trends in the start of the growing season in Fennoscandia 1982–2011. *Remote Sensing* 5: 4304-4318. https://doi.org/10.3390/rs5094304

Holmgaard SB, Thuestad AE, Myrvoll ER & Barlindhaug S (2018) Monitoring and managing human stressors to coastal cultural heritage in Svalbard. *Humanities* 8: 21. https://doi.org/10.3390/h8010021

Horstkotte T, Sandström C & Moen J (2014) Exploring the multiple use of boreal landscapes in northern Sweden: The importance of social-ecological diversity for mobility and flexibility. *Human Ecology* 42: 671–682. https://doi.org/10.1007/s10745-014-9687-z

Horstkotte T, Utsi TA, Larsson- Blind Å, Burgess P, Johansen B, Käyhkö J, Oksanen L & Forbes BC (2017) Human-animal agency in reindeer management: Sámi herders' perspectives on vegetation dynamics under climate change. *Ecosphere* 8: e01931. https://doi.org/10.1002/ecs2.1931

Horstkotte T, Lépy É & Risvoll C (Eds) (2020) *Supplementary Feeding in Reindeer Husbandry: Results from a Workshop with Reindeer Herders and Researchers from Norway, Sweden and Finland*. Umeå University, Umeå. http://umu.diva-portal.org/smash/get/diva2:1514960/FULLTEXT01.pdf

Hovelsrud GK, Poppel B, van Oort BEH & Reist JD (2011) Arctic societies, cultures, and peoples in a changing cryosphere. *In*: *Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere*, pp. 10-1–10-39. Arctic Monitoring and Assessment Programme, Oslo. https://www.amap.no/documents/doc/snow-water-ice-and-permafrost-in-the-arctic-swipa-climate-change-and-the-cryosphere/743

Hovelsrud GK, Kaltenborn BP & Olsen J (2020) Svalbard in transition: adaptations to cross-scale changes in Longyearbyen. *The Polar Journal*: 10: 420-442. https://doi.org/10.1080/2154896X.2020.1819016

Hovelsrud GK, Veland S, Kaltenborn B, Olsen J & Dannevig H (2021) Sustainable tourism in Svalbard: Balancing economic growth, sustainability, and environmental governance. *Polar Record* 57: E47. https://doi.org/10.1017/S0032247421000668

Hultine KR, Dettman DL, Williams DG, Puente R, English NB, Butterfield BJ & Búrquez A (2018) Relationships among climate, stem growth, and biomass δ^{13}C in the giant saguaro cactus (*Carnegiea gigantea*). *Ecosphere* 9: e02498. https://doi.org/10.1002/ecs2.2498

Huuskonen S, Domisch T, Finér L, Hantula J, Hynynen J, Matala J, Miina J, Neuvonen S, Nevalainen S, Niemistö P, Nikula A, Piri T, Siitonen J, Smolander A, Tonteri T, Uotila K &

Viiri H (2021) What is the potential for replacing monocultures with mixed-species stands to enhance ecosystem services in boreal forests in Fennoscandia? *Forest Ecology and Management* 479: 118558. https://doi.org/10.1016/j.foreco.2020.118558

Hvidsten D, Frafjord K, Gray JS, Henningsson AJ, Jenkins A, Kristiansen BE, Lager M, Rognerud B, Slåtsve AM, Stordal F, Stuen S & Wilhelmsson P. (2020) The distribution limit of the common tick, *Ixodes ricinus*, and some associated pathogens in north-western Europe. *Ticks and Tick-borne Diseases* 11: 101388. https://doi.org/10.1016/j.ttbdis.2020.101388

Hyvärinen E, Juslén A, Kemppainen E, Uddström A & Liukko UM (Eds) (2019). *The 2019 Red list of Finnish species*. Ympäristöministeriö & Suomen ympäristökeskus, Helsinki.https://hdl.handle.net/10138/299501

Icelandic Institute of Natural History (2018) *Válisti æðplantna* (*Red List for Vascular Plants*). https://www.ni.is/node/27225

Iden K, Kristiansen S, Mamen J, Szewczyk-Bartnicka H & Tajet HTT (2012) Været i Norge. Klimatologisk månedsoversikt desember 2012. *Met.no Info* 12/2012, 27 pp. Meteorological Institute of Norway, Oslo. https://www.met.no/publikasjoner/met-info/met-info-2012/_/attachment/download/c358d2fa-3dd2-4d9b-8910-a3d2a26eccaf:cace216deddbafc409bc33bff7b45f915717384b/MET-info-12-2012.pdf

Iizumi T, Shin Y, Kim W, Kim M & Choi J (2018) Global crop yield forecasting using seasonal climate information from a multi-model ensemble. *Climate Services* 11: 13-23. https://doi.org/10.1016/j.cliser.2018.06.003

IPBES (2019). *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Díaz S et al. (Eds). IPBES Secretariat, Bonn, Germany. 56 pp. https://doi.org/10.5281/zenodo.3553579

IPCC (2001) *Climate Change 1999: the Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge.

IPCC (2021) Summary for Policymakers. *In*: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds. Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock T K & Waterfield T, Yelekçi O, Yu R & Zhou B). Cambridge University Press, Cambridge. In Press.

Ito A, Reyer CPO, Gädeke A, Ciais P, Chang J, Chen M, François L, Forrest M, Hickler T, Ostberg S, Shi H, Thiery W & Tian H (2020) Pronounced and unavoidable impacts of low-end global warming on northern high-latitude land ecosystems. *Environmental Research Letters* 15: 044006. https://doi.org/10.1088/1748-9326/ab702b

Jackish R, Heincke BH, Zimmermann R, Sørensen EV, Pirttijärvi M, Kirsch M, Salmirinne H, Lode S, Kuronen U & Gloaguen R (2022) Drone-based magnetic and multispectral surveys to develop a 3D model for mineral exploration at Qullissat, Disko Island, Greenland. *Solid Earth* 13: 793-825. https://doi.org/10.5194/se-13-793-2022

Jakobsson S & Pedersen B (Eds) (2020) Naturindeks for Norge 2020. Tilstand og utvikling for biologisk mangfold. *NINA Rapport* 1886. 115 pp. Norwegian Institute for Nature Research, Trondheim. https://hdl.handle.net/11250/2686068

Jalkanen R (1997) Repeated red belts at Lusmavaara, western Lapland. *Finnish Forest Research Institute, Research Papers* 623: 91–95.

Janssen JAM, Rodwell JS, García Criado M et al. (in total 49 authors and 144 contributors) (2016) *European Red List of Habitats - Part 2. Terrestrial and freshwater habitats*. European Union.
https://ec.europa.eu/environment/nature/knowledge/pdf/terrestrial_EU_red_list_report.pdf

Jansson R, Nilsson C, Keskitalo ECH, Vlasova T, Sutinen ML, Moen J, Chapin FS III, Bråthen KA, Cabeza M, Callaghan TV, van Oort B, Dannevig H, Bay-Larsen IA, Ims RA & Aspholm PE (2015) Future changes in the supply of goods and services from natural ecosystems: Prospects for the European North. *Ecology and Society*: 20: https://doi.org/doi:10.5751/ES-07607-200332

Jensen GH, Madsen J, Johnson F & Tamstorf MP (2014) Snow conditions as an estimator of the breeding output in high-Arctic pink-footed geese *Anser brachyrhynchus*. *Polar Biology* 37: 1–14. https://doi.org/10.1007/s00300-013-1404-7

Jentsch A, Kreyling J & Beierkuhnlein C (2007) A new generation of climate-change experiments: events, not trends. *Frontiers in Ecology and the Environment* 5: 365-374. https://doi.org/10.1890/1540-9295(2007)5[365:ANGOCE]2.0.CO;2

Jentsch A, Kreyling J, Boettcher-Treschkow J & Beierkuhnlein C (2009) Beyond gradual warming: extreme weather events alter flower phenology of European grassland and heath species. *Global Change Biology* 15: 837-849. https://doi.org/10.1111/j.1365-2486.2008.01690.x

Jepsen JU, Hagen SB, Ims RA & Yoccoz NG (2008) Climate change and outbreaks of the geometrids *Operophtera brumata* and *Epirrita autumnata* in subarctic birch forest: evidence of a recent outbreak. *Journal of Animal Ecology* 77: 257-264. https://doi/10.1111/j.1365-2656.2007.01339.x

Jepsen JU, Hagen SB, Høgda KA, Ims RA, Karlsen SR, Tømmervik H & Yoccoz NG (2009) Monitoring the spatio-temporal dynamics of geometrid moth outbreaks in birch forest using MODIS-NDVI data. *Remote Sensing of Environment* 113:1939–1947. https://doi.org/10.1016/j.rse.2009.05.006

Jóhannesson GÞ & Lund KA (2017) Aurora Borealis: Choreographies of darkness and light. *Annals of Tourism Research* 63: 183-190. https://doi.org/10.1016/j.annals.2017.02.001

Jóhannsdóttir GE (2020) Methods for coastal flooding risk assessments. An overview of methods used in Scandinavia and the UK and a discussion of their suitability for Iceland. *Skýrsla* 2020-005. Veðurstofa Íslands, Reykjavik. https://en.vedur.is/media/vedurstofan-utgafa-2020/VI_2020_005.pdf

Jokinen P, Vajda A & Gregow H (2015) The benefits of emergency rescue and reanalysis data in decadal storm damage assessment studies. *Advances in Science and Research* 12: 97–101. https://doi.org/10.5194/asr-12-97-2015

Jones AR, Alleway HK, McAfee D, Reis-Santos P, Theuerkauf SJ & Jones R C (2022) Climate-friendly seafood: the potential for emissions reduction and carbon capture in marine aquaculture. *Bioscience* 72: 123-143. https://doi.org/10.1093/biosci/biab126

Jore S, Viljugrein H, Hofshagen M, Brun-Hansen H, Kristoffersen AB, Nygård K, Brun E, Ottesen P, Sævik BK & Ytrehus B (2011) Multi-source analysis reveals latitudinal and altitudinal shifts in range of *Ixodes ricinus* at its northern distribution limit. *Parasites & Vectors* 4: 84. https://doi.org/10.1186/1756-3305-4-84

Jore S, Vanwambeke SO, Viljugrein H, Isaksen K, Kristoffersen AB, Woldehiwet Z, Johansen B, Brun E, Brun-Hansen H, Westermann S, Larsen IL, Ytrehus B & Hofshagen M (2014) Climate and environmental change drives *Ixodes ricinus* geographical expansion at the northern range margin. *Parasites & Vectors* 7: 11. https://doi.org/10.1186/1756-3305-7-11

Jørgensen TJ (2019) Det arktiske guld. *Sermitsiaq AG*, Nuuk, Greenland. https://sermitsiaq.ag/node/210985

Kahle M, Kempf M, Martin B & Glaser R (2022) Classifying the 2021 'Ahrtal' flood event using hermeneutic interpretation, natural language processing, and instrumental data analyses. *Environmental Research Communications* 4: 051002. https://doi.org/10.1088/2515-7620/ac6657

Kahlén C, Andrén H, Månsson J & Sand H (2022) Using citizen data in a population model to estimate population size of moose (*Alces alces*). *Ecological Modelling* 471:110066. https://doi.org/10.1016/j.ecolmodel.2022.110066

Kaján E & Saarinen J (2013) Tourism, climate change and adaptation: A review. *Current Issues in Tourism* 16: 167-195. https://doi.org/10.1080/13683500.2013.774323

Kala CP, Singh SK, Rawat GS (2002) Effects of sheep and goat grazing on the species diversity in the alpine meadows of Western Himalaya. *The Environmentalist* 22: 183-189. https://doi.org/10.1023/A:1015306405212

Kalberer SR, Wisniewski M & Arora R (2006) Deacclimation and reacclimation of cold-hardy plants: Current understanding and emerging concepts. *Plant Science* 171: 3–16. https://doi.org/10.1016/j.plantsci.2006.02.013

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Kaltenborn BP & Emmelin L (1993) Tourism in the high north: Management challenges and recreation opportunity spectrum planning in Svalbard, Norway. *Environmental Management* 17: 41-50. https://doi.org/10.1007/BF02393793

Kaltenborn BP, Østreng W & Hovelsrud GK (2020) Change will be the constant – future environmental policy and governance challenges in Svalbard. *Polar Geography* 43: 25–45. https://doi.org/10.1080/1088937X.2019.1679269

Karlsen SR, Anderson H, van der Wal R & Hansen B (2018) A new NDVI measure that overcomes data sparsity in cloud-covered regions predicts annual variation in ground-based estimates of high arctic plant productivity. *Environmental Research Letters* 13: 025011. https://doi.org/10.1088/1748-9326/aa9f75

Karlson B, Andersen P, Arneborg L, Cembella A, Eikrem W, John U, West JJ, Klemm K, Kobos J, Lehtinen S, Lundholm N, Mazur-Marzech H, Naustvoll L, Poelman M, Provoost P, De Rijcke M & Suikkanen S (2021) Harmful algal blooms and their effects in coastal seas of Northern Europe. *Harmful Algae* 102: 101989. https://doi.org/10.1016/j.hal.2021.101989

Kautz LA, Martius O, Pfahl S, Pinto JG, Ramos AM, Sousa PM & Woollings T (2022) Atmospheric blocking and weather extremes over the Euro-Atlantic sector – a review. *Weather and Climate Dynamics* 3: 305–336. https://doi.org/10.5194/wcd-3-305-2022

Kharin VV, Flato GM, Zhang X, Gillett NP, Zwiers F & Anderson KJ (2018) Risks from climate extremes change differently from 1.5 °C to 2.0 °C depending on rarity. *Earth's Future* 6: 704–715. https://doi.org/10.1002/2018ef000813

Kietäväinen A & Tuulentie S (2013) Tourism strategies and climate change: rhetoric at both strategic and grassroots levels about growth and sustainable development in Finland. *Journal of Sustainable Tourism* 21: 845-861. https://doi.org/10.1080/09669582.2012.750326

King MD, Howat IM, Candela SG, Noh MJ, Jeong S, Noël BPY, van den Broeke MR, Wouters B & Negrete A (2020) Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat. *Communication Earth & Environment*:1: 1. https://doi.org/10.1038/s43247-020-0001-2

Knudsen EM & Walsh JE (2016) Northern hemisphere storminess in the Norwegian Earth System Model (NorESM1-M). *Geoscientific Model Development* 9: 2335-2355. https://doi.org/10.5194/gmd-9-2335-2016

Kohler J, Brandt O, Johansson M & Callaghan TV (2006) A long-term Arctic snow depth record from Abisko, northern Sweden, 1913–2004. *Polar Research* 25: 91–113. https://doi.org/10.3402/polar.v25i2.6240

Kolstad AL, Austrheim G, Solberg EJ, De Vriendt L & Speed JDM (2018) Pervasive moose browsing in boreal forests alters successional trajectories by severely suppressing keystone species. *Ecosphere* 9: e02458. https://doi.org/10.1002/ecs2.2458

Kong Q, Zheng J, Fowler HJ, Ge Q & Xi J (2019) Climate change and summer thermal comfort in China. *Theoretical and Applied Climatology* 137: 1077–1088. https://doi.org/10.1007/s00704-018-2648-5

Konstali K & Sorteberg A (2022) Why has precipitation increased in the last 120 years in Norway? *Journal of Geophysical Research-Atmospheres* 127: e2021JD036234. https://doi.org/10.1029/2021JD036234

Kontula T & Raunio A (Eds) (2019) *Threatened Habitat Types in Finland 2018. Red List of Habitats. Results and Basis for Assessment*. The Finnish Environment 2/290, 254 p. Finnish Environment Institute and Ministry of the Environment, Helsinki. https://hdl.handle.net/10138/308426

Kopisto L, Virtanen T, Pekkanen K, Mikkola K & Kauhanen H (2008) Tunturimittarituhotutkimus Käsivarren alueella 2004–2007. *Metlan työraportteja - Working Papers of the Finnish Forest Research Institute* 76:1–24.

Korhonen KT, Ahola A, Heikkinen J, Henttonen HM, Hotanen J-P, Ihalainen A, Melin M, Pitkänen J, Räty M, Sirviö M & Strandström M (2021) Forests of Finland 2014–2018 and their development 1921–2018. *Silva Fennica* 55: 10662. https://doi.org/10.14214/sf.10662

Kristiansen S, Mamen J, Szewczyk-Bartnicka H & Tajet HTT (2013) Været i Norge. Klimatologisk månedsoversikt januar 2013. *Met.no Info* 01/2013, 16 pp. Meteorological Institute of Norway, Oslo. https://www.met.no/publikasjoner/met-info/met-info-2013/_/attachment/download/1e5f4f7e-ccb5-4512-bc28-4ebb70c98f78:26e7900cf6ef3fb14d1702cd08ac21051a16945b/MET-info-01-2013.pdf

Krogli IK, Devoli G, Colleuille H, Boje S, Sund M & Engen IK (2018) The Norwegian forecasting and warning service for rainfall- and snowmelt-induced landslides. *Natural Hazards and Earth System Sciences* 18: 1427-1450. https://doi.org/10.5194/nhess-18-1427-2018

Kroglund F, Finstad B, Stefansson SO, Nilsen TO, Kristensen T, Rosseland BO, Teien HC & Salbu, B (2007) Exposure to moderate acid water and aluminum reduces Atlantic salmon post-smolt survival. *Aquaculture* 273: 360-373. https://doi.org/10.1016/j.aquaculture.2007.10.018

Kullman L (1989) Cold-induced dieback of montane spruce forests in the Swedish Scandes – a modern analogue of paleoenvironmental processes. *New Phytologist* 113: 377-389. https://doi.org/10.1111/j.1469-8137.1989.tb02416.x

Kumpula J, Jokinen M, Siitari J, & Siitari S (2020) Talven 2019–2020 sää-, lumi- ja luonnonolosuhteiden poikkeuksellisuus ja vaikutukset poronhoitoon. *Luonnonvara- ja biotalouden tutkimus* 58/2020, 57 pp. Luonnonvarakeskus (LUKE), Helsinki. https://jukuri.luke.fi/handle/10024/546154

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Kwiatkowski L, Torres O, Bopp L, Aumont O, Chamberlain M, Christian JR, Dunne JP, Gehlen M, Ilyina T, John JG, Lenton A, Li H, Lovenduski NS, Orr JC, Palmieri J, Santana-Falcón Y, Schwinger J, Séférian R, Stock CA, Tagliabue A, Takano Y, Tjiputra J, Toyama K, Tsujino H, Watanabe M, Yamamoto A, Yool A & Ziehn T (2020) Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. *Biogeosciences* 17: 3439-3470. https://doi.org/10.5194/bg-17-3439-2020

Laaksonen M, Sajanti E, Sormunen JJ, Penttinen R, Hänninen J, Ruohomäki K, Sääksjärvi I, Vesterinen EJ, Vuorinen I, Hytönen J & Klemola T (2017) Crowdsourcing-based nationwide tick collection reveals the distribution of *Ixodes ricinus* and *I. persulcatus* and associated pathogens in Finland. *Emerging Microbes & Infections* 6: 1-7. https://doi.org/10.1038/emi.2017.17

Laaksonen S, Pusenius J, Kumpula J, Venäläinen A, Kortet R, Oksanen A & Hoberg E (2010) Climate change promotes the emergence of serious disease outbreaks of filarioid nematodes. *Ecohealth* 7: 7–13. https://10.1007/s10393-010-0308-z

Laidre KL, Stern H, Kovacs KM, Lowry L, Moore SE, Regehr EV, Ferguson SH, Wiig Ø, Boveng P, Angliss RP, Born EW, Litovka D, Quakenbush L, Lydersen C, Vongraven D & Ugarte F (2015) Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century. *Conservation Biology* 29: 724–737. https://doi.org/10.1111/cobi.12474

Landrum L & Holland MM (2020) Extremes become routine in an emerging new Arctic. *Nature Climate Change* 10: 1108-1115. https://doi.org/10.1038/s41558-020-0892-z

Langlet O (1929) Några egendomliga frosthärjningar i tallskog, jämte ett försök att klarlegga deras orsak. *Svenska Skogsföreningens Tidskrift* 27: 423-461.

Lavoie D, Lambert N, ben Mustapha S & van der Baaren A (2013) *Projections of future physical and biogeochemical conditions in the Northwest Atlantic from CMIP5 Global Climate Models*. Canadian Technical Report of Hydrography and Ocean Sciences 285. 172 pp. Fisheries and Oceans Canada, Mont-Joli.

Lavoie D, Lambert N, & Gilbert D (2019) Projections of Future Trends in Biogeochemical Conditions in the Northwest Atlantic Using CMIP5 Earth System Models. *Atmosphere-Ocean* 57: 18-40. https://doi.org/10.1080/07055900.2017.1401973

Lawrence D (2016) Klimaendring og fremtidige flommer i Norge. *NVE Rapport* 81/2016, 66 pp. Norges vassdrag- og energidirektorat, Oslo. https://publikasjoner.nve.no/rapport/2016/rapport2016_81.pdf

Lawson DA & Rands SA (2019) The effects of rainfall on plant–pollinator interactions. *Arthropod-Plant Interactions* 13: 561–569. https://doi.org/10.1007/s11829-019-09686-z

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Layton-Matthews K, Hansen BB, Grøtan V, Fuglei E & Loonen MJJE (2020) Contrasting consequences of climate change for migratory geese: Predation, density dependence and carryover effects offset benefits of high-arctic warming. *Global Change Biology* 26: 642-657. https://doi.org/10.1111/gcb.14773

Ledger ME & Milner AM (2015). Extreme events in running waters. *Freshwater Biology* 60: 2455-2460. https://doi.org/10.1111/fwb.12673

Lehtonen I, Ruosteenoja K, Venäläinen A & Gregow H (2014) The projected 21st century forest-fire risk in Finland under different greenhouse gas scenarios. *Boreal Environment Research* 19: 127-139. https://helda.helsinki.fi/bitstream/handle/10138/228540/ber19-2-127.pdf?sequence=1

Lehtonen I, Ruosteenoja K & Mäkelä A (2019) Suomen muuttuva ilmasto – tietoa sähkönsiirtojärjestelmän riskien arviointia varten. *Ilmatieteen laitos, Raportteja* 2019:2. Finnish Meteorological Institute, Helsinki, 34 pp. http://hdl.handle.net/10138/301521

Lehtonen I, Venäläinen A & Gregow H (2020) Ilmastonmuutoksen vaikutukset Suomessa metsänhoidon näkökulmasta (The impacts of climate change in Finland from the forest management viewpoint). *Ilmatieteen laitos, Raportteja* 2020:5. Finnish Meteorological Institute, Helsinki, 41 pp. http://hdl.handle.net/10138/319348

Lefebvre J, Gauthier G, Giroux JF, Reed A, Reed ET & Bélanger L (2017) The greater snowgoose *Anser caerulescens atlanticus*: managing an overabundant population. *Ambio* 46: 262–274. https://doi.org/10.1007/s13280-016-0887-1

Leibovici DG, Bylund, H, Björkman C, Tokarevich N, Thierfelder T, Evengård & Quegan S (2021) Associating land cover changes with patterns of incidences of climate-sensitive infections: an example on tick-borne diseases in the Nordic area. *International Journal of Environmental Research and Public Health* 18: 10963. https://doi.org/10.3390/ijerph182010963

Lembrechts JJ, Lenoir J, Roth N, Hattab T, Milbau A, Haider S, Pellissier L, Pauchard A, Ratier Backes A, Dimarco RD, Nuñez MA, Aalto J & Nijs I (2019) Comparing temperature data sources for use in species distribution models: from in-situ logging to remote sensing. *Global Ecology and Biogeography* 28: 1578–1596. https://doi.org/10.1111/geb.12974

Lembrechts JJ, van den Hoogen J et al. (in total 405 authors) (2022) Global maps of soil temperature. *Global Change Biology* 28: 3110–3144. https://doi.org/10.1111/gcb.16060

Lemelin H, Dawson J, Stewart EJ., Maher P & Lueck M (2010) Last-chance tourism: the boom, doom, and gloom of visiting vanishing destinations. *Current Issues in Tourism* 13: 477-493. https://doi.org/10.1080/13683500903406367

Levis S, Foley JA & Pollard D (2000) Large-scale vegetation feedbacks on a doubled CO_2 climate. *Journal of Climate* 13: 1313-1325. https://doi.org/10.1175/1520-0442(2000)013%3C1313:LSVFOA%3E2.0.CO;2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Lind S, Ingvaldsen RB & Furevik T (2018) Arctic warming hotspot in the northern Barents Sea linked to declining sea-ice import. *Nature Climate Change* 8: 634-639. https://doi.org/10.1038/s41558-018-0205-y

Lindberg H, Aakala T & Vanha-Majamaa I (2021) Moisture content variation of ground vegetation fuels in boreal mesic and sub-xeric mineral soil forests in Finland. *International Journal of Wildland Fire* 30: 283-293. https://doi.org/10.1071/WF20085

Lindström Å, Green M, Husby M, Kålås JA, Lehikoinen A & Stjernman M (2019) Population trends of waders on their boreal and arctic breeding grounds in northern Europe. *Wader Study* 126: 200–216. https://doi.org/10.18194/ws.00167

Liu Y, & vanhauwaer Bjelland H (2014) Estimating costs of sea lice control strategy in Norway. *Preventive Veterinary Medicine* 117: 469-477. https://doi.org/10.1016/j.prevetmed.2014.08.018

Löf A, Sandström P, Baer K, Stinnerbom M & Sandström C (2012) Renskötsel och klimatförändring: Risker, sårbarhet och anpassningsmöjligheter i Vilhelmina norra sameby. *Forskningsrapporter i statsvetenskap vid Umeå universitet* 4/2012, 48 pp. Umeå University, Umeå. https://umu.diva-portal.org/smash/get/diva2:552672/FULLTEXT02.pdf

Løkken JO, Hofgaard A, Dalen L & Hytteborn H (2019) Grazing and warming effects on shrub growth and plant species composition in subalpine dry tundra: An experimental approach. *Journal of Vegetation Science* 30: 698-708. https://doi.org/10.1111/jvs.12752

Long WC, Swiney KM, Harris C, Page HN & Foy RJ (2013) Effects of ocean acidification on juvenile red king crab (*Paralithodes camtschaticus*) and Tanner crab (*Chionoecetes bairdi*) growth, condition, calcification, and survival. *PloS One* 8: e60959. https://doi.org/10.1371/journal.pone.0060959

López-Blanco E, Lund M, Williams M, Tamstorf MP, Westergaard-Nielsen A, Exbrayat JF, Hansen BU & Christensen TR (2017) Exchange of CO_2 in Arctic tundra: impacts of meteorological variations and biological disturbance. *Biogeosciences* 14: 4467–4483 https://doi.org/10.5194/bg-14-4467-2017

López-Blanco E, Jackowicz-Korczynski M A, Mastepanov M, Skov K, Westergaard-Nielsen A, Williams M & Christensen TR (2020) Multi-year data-model evaluation reveals the importance of nutrient availability over climate in arctic ecosystem C dynamics. *Environmental Research Letters* 15: 094007. https://doi.org/10.1088/1748-9326/ab865b

López-Blanco E, Langen PL, Williams M, Christensen JH, Boberg F, Langley K, Christensen TR (2022) The future of tundra carbon storage in Greenland – sensitivity to climate and plant trait changes. *Science of The Total Environment* 846: 157385. https://doi.org/10.1016/j.scitotenv.2022.157385

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Losapio G, Cerabolini BEL, Maffioleffi C, Tampucci D, Gobbi M & Caccianiga M (2021) The consequences of glacier retreat are uneven between plant species. *Frontiers in Ecology and Evolution* 8: 616562. https://10.3389/fevo.2020.616562

Ludwig GX, Alatalo RV, Helle P, Lindén H, Lindström J & Siitari H (2006) Short- and long-term population dynamical consequences of asymmetric climate change in black grouse. *Proceedings of the Royal Society B: Biological Sciences* 273: 2009–2016. https://doi.org/10.1098/rspb.2006.3538

Lund M, Raundrup K, Westergaard-Nielsen A, López-Blanco E, Nymand J & Aastrup P (2017) Larval outbreaks in West Greenland: Instant and subsequent effects on tundra ecosystem productivity and CO_2 exchange. *Ambio* 46: S26-S38. https://10.1007/s13280-016-0863-9

Luomaranta A, Aalto J & Jylhä K (2019) Snow cover trends in Finland over 1961-2004 based on gridded snow depth observations. *International Journal of Climatology* 39: 3147–3159. https://doi.org/10.1002/joc.6007

Lupo AR (2020) Atmospheric blocking events: a review. *Annals of the New York Academy of Sciences* 1504: 5-24. https://doi.org/10.1111/nyas.14557

Lupo AR, Kononova NK, Semenova IG & Lebedeva MG (2022) A comparison of the characteristics of drought during the late 20th and early 21st centuries over Eastern Europe, Western Russia and Central North America. *Atmospheres* 12: 1033. https://doi.org/10.3390/atmos12081033

Lussana C, Tveito OE & Uboldi F (2018) Three-dimensional spatial interpolation of 2 m temperature over Norway. *Quarterly Journal of the Royal Meteorological Society* 144: 344-364. https://doi.org/10.1002/qj.3208

MacLean SA & Beissinger SR (2017) Species' traits as predictors of range shifts under contemporary climate change: a review and meta-analysis. *Global Change Biology* 4094–4105. https://doi.org/10.1111/gcb.13736

Madslien K, Ytrehus B, Vikøren T, Malmsten J, Isaksen K, Hygen HO & Solberg EJ (2011) Hair-loss epizootic in moose (*Alces alces*) associated with massive deer ked (*Lipoptena cervi*) infestation. *Journal of Wildlife Diseases* 47: 893–906. https://doi.org/10.7589/0090-3558-47.4.893

Madslien K, Ytrehus B, Viljugrein H, Solberg EJ, Bråten KR & Mysterud A (2012) Factors affecting deer ked (*Lipoptena cervi*) prevalence and infestation intensity in moose (*Alces alces*) in Norway. *Parasites & Vectors* 5: 251. https://doi.org/10.1186/1756-3305-5-251

Man R, Lu P & Dang QL (2020) Cold tolerance of black spruce, white spruce, jack pine, and lodgepole pine seedlings at different stages of spring dehardening. *New Forests* 52: 317–328. https://doi.org/10.1007/s11056-020-09796-0

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Månsson J, Kalén C, Kjellander P, Andrén H, Smith H (2007) Quantitative estimates of tree species selectivity by moose (*Alces alces*) in a forest landscape. *Scandinavian Journal of Forest Research* 22: 407–414. https://doi.org/10.1080/02827580701515023

Månsson J, Nilsson L, Felton AM & Jarnemo A (2021) Habitat and crop selection by red deer in two different landscape types. *Agriculture, Ecosystems & Environment* 318: 107483. https://doi.org/10.1016/j.agee.2021.107483

Marshall GJ, Vignols RM & Rees WG (2016) Climate change in the Kola Peninsula, Arctic Russia, during the last 50 years from meteorological observations. *Journal of Climate* 29: 6823-6840. https://doi.org/10.1175/JCLI-D-16-0179.1

Marshall GJ, Jylhä K, Kivinen S, Laapas M & Dyrrdal AV (2020) The role of atmospheric circulation patterns in driving recent changes in indices of extreme seasonal precipitation across Arctic Fennoscandia. *Climatic Change* 162: 741–759. https://doi.org/10.1007/s10584-020-02747-w

Mason WL, Diaci J, Carvalho J & Valkonen S (2022) Continuous cover forestry in Europe: usage and the knowledge gaps and challenges to wider adoption, *Forestry* 95: 1–12. https://doi.org/10.1093/forestry/cpab038

Matala J (2020) Hirvieläintuhot muuttuvassa ilmastossa. (Cervid damage in a changing climate). *Metsätieteen aikakauskirja vuosikerta* 2020: 10497. https://doi.org/10.14214/ma.10497

Mathisen IE, Mikheeva A, Tutubalina OV, Aune S & Hofgaard A (2014) Fifty years of tree line change in the Khibiny Mountains,Russia: advantages of combined remote sensing and dendroecological approaches. *Applied Vegetation Science* 17: 6-16. https://doi.org/10.1111/avsc.12038

Mattila O, Hayrinen L, Tervo M, Toppinen A & Berghall S (2015) Challenges of municipal greening and multifunctional forest management: the case of Finland. *Urban Forestry & Urban Greening* 14: 982-990. https://doi.org/10.1016/j.ufug.2015.09.007

Meier WN, Perovich D, Farell S, Haas, C, Hendricks S, Petty AA, Webster M, Divine D, Gerland S, Kaleschke L, Ricker R, Steer A, Tian-Kunze X, Tschudi M & Wood K (2021) Sea Ice. *In*: *Arctic Report Card 2021* (Eds. Moon TA, Drucknemiller ML & Thoman RL). https://doi.org/10.25923/y2wd-fn85

Mendez T (2010) Thin ice, shifting geopolitics: The legal implications of Arctic ice melt. *Denver Journal of International Law & Policy* 38: 527-547.

Meredith M, Sommerkorn M, Cassotta S, Derksen C, Ekaykin A, Hollowed A, Kofinas G, Mackintosh A, Melbourne-Thomas J, Muelbert MMC, Ottersen G, Pritchard H & Schuur EAG (2019) Polar Regions. *In*: Pörtner HO, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Alegría A, Nicolai M, Okem A, Petzold J, Rama B & Weyer NM (eds.): *IPCC Special Report on the Ocean and Cryosphere in a Changing*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Climate. Cambridge University Press, Cambridge, UK & New York, NY, USA, pp. 203-320. https://doi.org/10.1017/9781009157964.005

Mernild SH, Hanna E, McConnell JR, Sigl M, Beckerman AP, Yde JC, Cappelen J, Malmros JK & Steffen K (2015) Greenland precipitation trends in a long-term instrumental climate context (1890–2012): evaluation of coastal and ice core records. *International Journal of Climatology* 35: 303-320. https://doi.org/10.1002/joc.3986

Meteorological Institute of Norway (2021) *Nord-Norge siden 1900*. https://www.met.no/vaer-og-klima/klima-siste-150-ar/regionale-kurver/nord-norge-siden-1900 (last changed 20 January 2021).

Meteorological Institute of Norway (2022) *Real-time Snow Depth Observations*. https://cryo.met.no/en/snow-depth-products

Mienna IM, Austrheim G, Klanderud K, Bollandsås OM & Speed JDM (2022) Legacy effects of herbivory on treeline dynamics along an elevational gradient. *Oecologia* 198: 801-814. https://doi.org/10.1007/s00442-022-05125-8

Mikusiński G, Orlikowksa EH, Bubnicki JW, Jonsson BG & Svensson J (2021) Strengthening the network of high conservation value forests in boreal landscapes. *Frontiers in Ecology and Evolution* 8: 595730. https://doi.org/*10.3389/*fevo.2020.595730

Ministry of Climate and Environment of Norway (2021) Klimaplan for 2021–2030. *Meld. St.* 13 (2020-2021). Parliament of Norway. https://www.regjeringen.no/no/dokumenter/meld.-st.-13-20202021/id2827405/

Ministry of Petroleum and Energy of Norway (2021). *Åpningsprosess for undersøkelse og utvinning av havbunnsmineraler på norsk kontinentalsokkel: Forslag til program for konsekvensutredning etter havbunnsmineralloven*. Høringsdokument Olje- og Energiepartementet, Norway. https://www.regjeringen.no/contentassets/a3dd0ce426a14e25abd8b55154f34f20/forslag-til-konsekvensutredningsprogram-l1205562.pdf

Moen A (1999) *National atlas of Norway - Vegetation*. Norwegian Mapping Authority, Hønefoss.

Moeslund JE, Nygaard B, Ejrnæs R, Bell N, Bruun LD, Bygebjerg R, Carl H, Damgaard J, Dylmer E, Elmeros M, Flensted K, Fog K, Goldberg I, Gønget H, Helsing F, Holmen M, Jørum P, Lissner J, Læssøe T, Madsen HB, Misser J, Møller PR, Nielsen OF, Olsen K, Sterup J, Søchting U, Wiberg-Larsen P & Wind P (2019) *Den Danske Rødliste*. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi. www.redlist.au.dk

Moon TA, Redesco M, Box JE, Cappelen J, Fausto RS, Fettweis X, Korsgaard NJ, Loomis BD, Mankoff KD, Mote TL, Wehrlé A & Winton ØA (2021) Greenland Ice Sheet. *In*: *Arctic Report Card 2021* (Eds. Moon TA, Drucknemiller ML & Thoman RL). https://doi.org/10.25923/546g-ms61

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Moore GWK (2016) The December 2015 North Pole warming event and the increasing occurrence of such events. *Scientific Reports* 6: 39084. https://doi.org/10.1038/srep39084

Moraru A, Pavlicek M, Bruland O & Ruther N (2021) The story of a steep river: causes and effects of the flash flood on 24 July 2017 in Western Norway. *Water* 13: 1688. https://doi.org/10.3390/w13121688

Mota VC, Nilsen TO, Gerwins J, Gallo M, Ytteborg E, Baeverfjord G, Kolarevic J, Summerfelt ST & Terjesen BF (2019) The effects of carbon dioxide on growth performance, welfare, and health of Atlantic salmon post-smolt (*Salmo salar*) in recirculating aquaculture systems. *Aquaculture* 498: 578-586. https://doi.org/10.1016/j.aquaculture.2018.08.075

Mota VC, Nilsen TO, Gerwins J, Gallo M, Kolarevic J, Krasnov A & Terjesen BF (2020) Molecular and physiological responses to long-term carbon dioxide exposure in Atlantic salmon (*Salmo salar*). *Aquaculture* 519: 734715. https://doi.org/10.1016/j.aquaculture.2019.734715

Mudryk L, Santolaria-Otin M, Krinner G, Menegoz M Derksen C Brutel-Vuilmet C Brady M & Essery R (2020) Historical Northern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble. *Cryosphere* 14: 2495-2514. https://doi.org/10.5194/tc-14-2495-2020

Mudryk L, Chereque AE, Derksen C, Luojus K & Decharme B (2021) Terrestrial snow cover. *In*: *Arctic Report Card 2021* (Eds. Moon TA, Drucknemiller ML & Thoman RL). https://doi.org/10.25923/16xy-9h55

Müller DK & Huuva SK (2009) Limits to Sami tourism development: the case of Jokkmokk, Sweden. *Journal of Ecotourism* 8: 115-127. https://doi.org/10.1080/14724040802696015

Myhre G, Alterskjær K, Stjern CW, Hodnebrog ML, Samset BH & Stohl A (2019). Frequency of extreme precipitation increases extensively with event rareness under global warming. *Scientific Reports* 9: 2–11. https://doi.org/10.1038/s41598-019-52277-4

Mysterud A, Madslien K, Herland A, Viljugrein H & Ytrehus B (2016) Phenology of deer ked (*Lipoptena cervi*) host-seeking flight activity and its relationship with prevailing autumn weather. *Parasites & Vectors* 9: 95. https://doi.org/10.1186/s13071-016-1387-7

Näkkäläjärvi K, Juntunen S & Jaakkola J (2020). SAAMI – Saamelaisten sopeutuminen ilmastonmuutokseen – hankkeen tieteellinen loppuraportti. *Valtioneuvoston selvitys- ja tutkimustoiminnan julkaisusarja* 2020/25, 405 pp. Valtioneuvosto, Helsinki. http://urn.fi/URN:ISBN:978-952-287-930-1

NASA (2022) *GISS Surface Temperature Analysis* (v4). Goddard Institute for Space Studies, National Aeronautics and Space Administration. https://data.giss.nasa.gov/gistemp/maps/index_v4.html

National Academies of Sciences, Engineering, and Medicine (2016) *Attribution of Extreme Weather Events in the Context of Climate Change*. The National Academies Press, Washington, DC. https://doi.org/10.17226/21852

Nettier B, Dobremez L & Brunschwig G (2015) Prendre en compte les interactions entre alpages et exploitations dans les systèmes agropastoraux : une revue bibliographique. *INRA Productions Animales* 28: 329-339. https://doi.org/10.20870/productions-animales.2015.28.4.3037

Neuvonen S & Viiri H (2017) Changing climate and outbreaks of forest pest insects in a cold northern country, Finland. *In*: Latola K & Savola H (Eds.): *The interconnected Arctic*, pp. 49-60. Springer Polar Sciences, Springer International Publishing AG, Cham. https://doi.org/10.1007/978-3-319-57532-2

Neuvonen S, Bylund H & Tømmervik H (2005) Forest defoliation risks in birch forest by insects under different climate and land use scenarios in northern Europe. *In*: Wielgolaski FE (Ed): *Plant ecology, herbivory, and human impact in Nordic mountain birch forests*, pp. 125–138. Springer, New York.

Nevalainen S, Sirkiä S, Peltoniemi S, Neuvonen S (2015) Vulnerability to pine sawfly damage decreases with site fertility but the opposite is true with *Scleroderris* canker damage; results from Finnish ICP Forests and NFI data. *Annals of Forest Science* 72: 909–917. https://doi.org/10.1007/s13595-014-0435-8

Nilsen IB, Hanssen- Bauer I, Tveito OE & Wong WK (2020) Projected changes in days with zero-crossings for Norway. *International Journal of Climatology* 41: 2173–2188. https://doi.org/10.1002/joc.6913

Nilsson C, Polvi LE & Lind L (2015) Extreme events in streams and rivers in arctic and subarctic regions in an uncertain future. *Freswater Biology* 60: 2535-2546. https://doi.org/10.1111/fwb.12477

Nordmøre museum 2021. *Postkort "4361 fra fjellet" med motiv av geiter oppe i fjellheimen. Ukjent lokasjon og datering, men trolig fra Møre og Romsdal eller Oppdal. Kortet er utgitt ved Normanns kunstforlag A/S, Oslo. Fra Nordmøre Museums fotosamlinger*. Stiftelsen Nordmøre museum, Kristiansund. https://digitaltmuseum.no/021016564059/postkort-4361-fra-fjellet-med-motiv-av-geiter-oppe-i-fjellheimen-ukjent

Norwegian Environmental Agency (2022) *Nature Index for Norway*. https://naturindeks.no/

Norwegian Climate Service Centre (2022) Observations and weather statistics. https://seklima.met.no/observations/

Nuttall M (2022) Wild lands, remote edges: formations and abstractions in Greenland’s resource zones. *In*: Mason A (Ed.): *Arctic Abstractive Industry: Assembling the Valuable and Vulnerable North*, pp. 83-107. Berghahn Books, New York.

Nystad ME & Gaup BS (2021) *40 rein gikk gjennom isen og druknet*. Norwegian Broadcasting Corporation. https://www.nrk.no/sapmi/40-reinsdyr-gikk-gjennom-isen-og-druknet-i-kautokeinoelva-1.15723334

Ocobock C, Turunen M, Soppela P & Rasmus S (2022) The impact of winter warming and more frequent icing events on reindeer herder occupational safety, health, and wellbeing. *American Journal of Human Biology* e23790. https://doi.org/10.1002/ajhb.23790

O'Gorman PA (2015) Precipitation extremes under climate change. *Current Climate Change Reports* 1: 49–59. https://doi.org/10.1007/s40641-015-0009-3

Ögren E (1996) Premature dehardening in *Vaccinium myrtillus* during a mild winter: a cause for winter dieback? *Functional Ecology* 10: 724-732.

Ögren E, Nilsson T & Sundblad LG (1997) Relationship between respiratory depletion of sugars and loss of cold hardiness in coniferous seedlings over-wintering at raised temperatures: indications of different sensitivities of spruce and pine. *Plant, Cell and Environment* 20: 247-253.

Ólafsdóttir R, Tuulentie S, Hovgaard G, Zinglersen KB, Svartá M, Poulsen HH & Søndergaard M (2020) The contradictory role of tourism in the northern peripheries: Overcrowding, overtourism and the importance of tourism for rural development. *In*: McDonagh J & Tuulentie S (Eds.): *Sharing Knowledge for Land Use Management: Decision-Making and Expertise in Europe's Northern Periphery*, pp. 86-99. Edward Elgar Publishing Ltd, Cheltenham.

Olafsson H & Rousta I (2021) Influence of atmospheric patterns and North Atlantic Oscillation (NAO) on vegetation dynamics in Iceland using remote sensing. *European Journal of Remote Sensing* 54: 351-363. https://doi.org/10.1080/22797254.2021.1931462

Ólafsson H, Furger M & Brümmer B (2007) The weather and climate of Iceland. *Meteorologische Zeitschrift* 16, 1: 5-8. (+ additional articles in the same issue)

Oliver EC, Benthuysen JA, Bindoff NL, Hobday AJ, Holbrook NJ, Mundy CN & Perkins-Kirkpatrick SE (2017) The unprecedented 2015/16 Tasman Sea marine heatwave. *Nature Communications*, 8: 16101. https://doi.org/10.1038/ncomms16101

Olofsson J, Tømmervik H & Callaghan TV (2012) Vole and lemming activity observed from space. *Nature Climate Change* 2: 880–883. https://doi.org/10.1038/nclimate1537

Olofsson J, te Beest M & Ericson L (2013) Complex biotic interactions drive long-term vegetation dynamics in a subarctic ecosystem. *Philosophical Transactions of the Royal Society, B, Biological Sciences* 368: 20120486. https://doi:10.1098/rstb.2012.0486

O'Neill BC, Tebaldi C, van Vuuren DP, Eyring V, Friedlingstein P, Hurtt G, Knutti R, Kriegler E, Lamarque JF, Lowe J, Meehl GA, Moss R, Riahi K & Sanderson BM (2016) The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development* 9: 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Oskal MBS, Balto P, Eriksen AM & Grønmo SF (2022). *Ny beitekrise i reindriften: – Det er tungt*. Norwegian Broadcasting Corporation. https://www.nrk.no/sapmi/ny-beitekrise-i-reindriften-pa-grunn-av-klimaendringene_-_-det-er-tungt_-sier-reineier-1.15797336

Osuch M, Wawrzyniak T & Łepkowska E (2022) Changes in the flow regime of high Arctic catchments with different stages of glaciation, SW Spitsbergen. *Science of the Total Environment* 817: 152924. https://doi.org/10.1016/j.scitotenv.2022.152924

Overland J, Walsh J & Kattsov V (2017). Trends and feedbacks. *In*: *Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017*, pp. 9-23. Arctic Monitoring and Assessment Programme, Oslo. https://www.amap.no/documents/doc/snow-water-ice-and-permafrost-in-the-arctic-swipa-2017/1610

Pääkkö E, Mäkelä K, Saikkonen A, Tynys S, Anttonen M, Johansson P, Kumpula J, Mikkola K, Norokorpi Y, Suominen O, Turunen M, Virtanen R & Väre H (2018) Tunturit. *In*: Kontula T & Raunio A (Eds.): *Suomen luontotyyppien uhanalaisuus 2018. Luontotyyppien punainen kirja. Osa 1 – tulokset ja arvioinnin perusteet* (Threatened Habitat Types in Finland 2018. Red Book of Habitats. Part 1 – results and basis of the assessment). Suomen ympäristö 5/2018: 255–313. Ympäristökeskus ja Ympäristöministeriö, Helsinki. http://urn.fi/URN:ISBN:978-952-11-4816-3

Palahi M, Valbuena R, Senf C, Acil N, Pugh TAM, Sadler J, Seidl R, Potapov P, Gardiner B, Hetemaki L, Chirici G, Francini S, Hlasny T, Lerink BJW, Olsson H, Olabarria JRG, Ascoli D, Asikainen A, Bauhus J, Berndes G, Donis J, Fridman J, Hanewinkel M, Jactel H, Lindner M, Marchetti M, Marusak R, Sheil D, Tome M, Trasobares A, Verkerk PJ, Korhonen M & Nabuurs GJ (2021) Concerns about reported harvests in European forests. *Nature* 592: E15-E17. https://doi.org/10.1038/s41586-021-03292-x

Paulsen M (2021) *Dilemmaet tilleggsfôring: En nymateralistisk studie av tilleggsfôring av rein*. PhD thesis, Nord University, Bodø.

Pedretti D & Irannezhad M (2019) Non-stationary peaks-over-threshold analysis of extreme precipitation events in Finland, 1961-2016. *International Journal of Climatology* 39: 1128-1143. https://doi.org/10.1002/joc.5867

Peeters B, Pedersen ÅØ, Loe LE, Isaksen K, Veiberg V, Stien A, Kohler J, Gallet JC, Aanes R & Hansen BB (2019) Spatiotemporal patterns of rain-on-snow and basal ice in high Arctic Svalbard: detection of a climate-cryosphere regime shift. *Environmental Resarch Letters* 14: 015002. https://doi.org/10.1088/1748-9326/aaefb3

Petersen GN (2021) Trends in soil temperature in the Icelandic highlands from 1977 to 2019. *International Journal of Climatology* 42: 2299-2310. https://doi.org/10.1002/joc.7366

Piao S, Wang X, Park T, Chen C, Lian X, He Y, Bjerke JW, Chen A, Ciais P, Tømmervik H, Nemani RR & Myneni R (2020) Characteristics, drivers and feedbacks of global greening.

Nature Reviews Earth & Environment 1: 14–27. https://doi.org/doi:10.1038/s43017-019-0001-x

Platts PJ, Mason SC, Palmer G, Hill JK, Oliver TH, Powney GD, Fox R & Thomas CD (2019) Habitat availability explains variation in climate-driven range shifts across multiple taxonomic groups. *Scientific Reports* 9: 15039. https://doi.org/10.1038/s41598-019-51582-2

Potterf M, Eyvindson K, Blattert C, Burgas D, Burner R, Stephan JG & Mönkkönen M (2022) Interpreting wind damage risk – how multifunctional forest management impacts standing timber at risk of wind felling. *European Journal of Forest Research* 141: 347–361. https://doi.org/10.1007/s10342-022-01442-y

Potthoff K (2017) Spatio-temporal patterns of birch regrowth in a Western Norwegian treeline ecotone. *Landscape Research* 42: 63-77.

Prebensen NK (2007) Exploring tourists' images of a distant destination. *Tourism Management* 28: 747-756. https://doi.org/10.1016/j.tourman.2006.05.005

Prowse TD, Bring A, Carmack EC, Holland MM, Instanes A, Mård J, Vihma T & Wrona FJ (2017). Freshwater. *In*: *Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017*, pp. 169-202. Arctic Monitoring and Assessment Programme, Oslo. https://www.amap.no/documents/doc/snow-water-ice-and-permafrost-in-the-arctic-swipa-2017/1610

Prytz N, Nordbø FS, Higham JDR & Thornam H (2018). Utredning om konsekvenser for Norge av klimaendringer i andre land. *Miljødirektoratet Rapport* M-932, 100 pp. https://www.miljodirektoratet.no/globalassets/publikasjoner/m932/m932.pdf

Rachlewicz G (2009) River floods in glacier-covered catchments of the High Arctic: Billefjorden-Wijdefjorden, Svalbard. *Norsk Geografisk Tidsskrift – Norwegian Journal of Geography* 63: 115-122. https://doi.org/10.1080/00291950902907835

Rankinen K, Bernal JEC, Homberg M, Vuorio K & Granlund K (2018) Identifying multiple stressors that influence eutrophication in a Finnish agricultural river. *Science of the Total Environment* 658: 1278–1292. https://doi.org/10.1016/j.scitotenv.2018.12.294

Räsänen A (2022) Cross-scale interactions in flood risk management: A case study from Rovaniemi, Finland. *International Journal of Disaster Risk Reduction* 57: 102185. https://doi.org/10.1016/j.ijdrr.2021.102185

Räsänen A, Kauppinen V, Juhola S, Setten G & Lein H (2020) Configurations of community in flood risk management, *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography*: 74: 165-180. https://doi.org/10.1080/00291951.2020.1754285

Rasmus S, Kivinen S & Irannezhad M (2018) Basal ice formation in snow cover in northern Finland between 1948 and 2016. *Environmental Research Letters* 13: 114009. https://doi.org/10.1088/1748-9326/aae541

Rasmus S, Turunen M, Luomaranta A, Kivinen S, Jylhä K & Räihä J (2020) Climate change and reindeer management in Finland: Co-analysis of practitioner knowledge and meteorological data for better adaption. *Science of the Total Environment* 710: 136229. https://doi.org/10.1016/j.scitotenv.2019.136229

Rasmus S, Wallen H, Turunen M, Landauer M, Tahkola J, Jokinen M & Laaksonen S (2021) Land-use and climate related drivers of change in the reindeer management system in Finland: geography of perceptions. *Applied Geography* 134: 102501. https://doi.org/10.1016/j.apgeog.2021.102501

Remen M, Oppedal F, Torgersen T, Imsland AK & Olsen RE (2012) Effects of cyclic environmental hypoxia on physiology and feed intake of post-smolt Atlantic salmon: initial responses and acclimation. *Aquaculture* 326: 148-155. https://doi.org/10.1016/j.aquaculture.2011.11.036

Remen M, Oppedal F, Imsland AK, Olsen RE & Torgersen T (2013) Hypoxia tolerance thresholds for post-smolt Atlantic salmon: dependency of temperature and hypoxia acclimation. *Aquaculture* 416: 41-47. https://doi.org/10.1016/j.aquaculture.2013.08.024

Remen M, Sievers M, Torgersen T & Oppedal F (2016) The oxygen threshold for maximal feed intake of Atlantic salmon post-smolts is highly temperature-dependent. *Aquaculture* 464: 582-592. https://doi.org/10.1016/j.aquaculture.2016.07.037

Renaud PE, Sejr MK, Bluhm BA, Sirenko B & Ellingsen IH (2015) The future of Arctic benthos: Expansion, invasion, and biodiversity. *Progress in Oceanography* 139: 244-257. https://doi.org/10.1016/j.pocean.2015.07.007

Rice H, Cohen S, Scott D & Steiger R (2022) Climate change risk in the Swedish ski industry. *Current Issues in Tourism* 25: 2805-2820. https://doi.org/10.1080/13683500.2021.1995338

Rikkonen P, Kotro J, Koistinen K, Penttilä K & Kauriinoja H (2013) Opportunities for local food suppliers to use locality as a competitive advantage – a mixed survey methods approach. *Acta Agriculturae Scandinavica B* 63: 29-37. https://doi.org/10.1080/09064710.2013.783620

Rinke A, Maturilli M, Graham RM, Matthes H, Handorf D, Cohen L, Hudson SR & Moore JC (2017) Extreme cyclone events in the Arctic: Wintertime variability and trends. *Environmental Research Letters* 12: 094006. https://doi.org/10.1088/1748-9326/aa7def

Rinne J, Tuovinen JP, Klemedtsson L, Aurela M, Holst J, Lohila A, Weslien P, Vestin P, Łakomiec P, Peichl M, Tuittila ES, Heiskanen L, Laurila T, Li X, Alekseychik P, Mammarella I, Ström L, Crill P & Nilsson MB (2020) Effect of the 2018 European drought on methane and carbon dioxide exchange of northern mire ecosystems. *Philosophical Transactions of the Royal Society, B, Biological Sciences* 375: 20190517. https://10.1098/rstb.2019.0517

Riseth JÅ, Tømmervik H & Bjerke JW (2016) 175 years of adaptation: North-Scandinavian Sámi reindeer herding between governmental policies and winter climate variability (1835-2010). *Journal of Forest Economics* 24: 186–204. https://doi.org/10.1016/j.jfe.2016.05.002

Ritz E, Bjerke JW & Tømmervik H (2020) Monitoring winter stress vulnerability of high-latitude understory vegetation using intraspecific trait variability and remote sensing approaches. *Sensors* 20: 2102. https://doi.org/10.3390/s20072102

Rixen C, Høye TT, Macek P, Aerts R, Alatalo J, Anderson JT, Arnold PA, Barrio IC, Bjerke JW, Björkman MP, Blok D, Blume-Werry G, Boike J, Bokhorst S, Carbognani M, Christiansen CT, Convey P, Cooper EJ, Cornelissen JHC, Coulson SJ, Dorrepaal E, Elberling B, Elmendorf SC, Elphinstone C, Forte TGW, Frei ER, Geange SR, Gehrmann F, Gibson C, Grogan P, Halbritter AH, Harte J, Henry GHR, Inouye DW, Irwin RE, Jespersen G, Jónsdóttir IS, Jung JY, Klinges DH, Kudo G, Lämsä J, Lee H, Lembrechts JJ, Lett S, Lynn JS, Mann HMR, Mastepanov M, Morse J, Myers-Smith IH, Olofsson J, Paavola R, Petraglia A, Phoenix GK, Semenchuk P, Siewert MB, Slatyer R, Spasojevic M, Suding K, Sullivan P, Thompson KL, Väisänen M, Vandvik V, Venn S, Walz J, Way R, Welker JM, Wipf S & Zong S (2022) Winters are changing: snow effects on Arctic and alpine tundra ecosystems. *Arctic Science*. https://doi.org/10.1139/AS-2020-0058

Rogers JC, Yang L & Li L (2005) The role of Fram Strait winter cyclones on sea ice flux and on Spitsbergen air temperatures, *Geophysical Research Letters* 32: L06709. https://doi.org/10.1029/2004GL022262

Rogers CDW, Kornhuber K, Perkins-Kirkpatrick SE, Loikith PC & Singh D (2022) Sixfold increase in historical Northern Hemisphere concurrent large heatwaves driven by warming and changing atmospheric circulations. *Journal of Climate* 35: 1063-1078. https://doi.org/10.1175/JCLI-D-21-0200.1

Ross LC, Austrheim G, Asheim LJ, Bjarnason G, Feilberg J, Fosaa AM, Hester AJ, Holand Ø, Jónsdóttir IS, Mortensen LE, Mysterud A, Olsen E, Skonhoft A, Speed JDM, Steinheim G, Thompson DBA & Thórhallsdóttir AG (2016) Sheep grazing in the North Atlantic region: A long-term perspective on environmental sustainability. *Ambio* 45: 551-566. https://doi.org/10.1007/s13280-016-0771-z

Rosving-Asvid A (2010) Catch history and status of the harbour seal (*Phoca vitulina*) in Greenland. *NAMMCO Scientific Publications* 8: 161–174. https://doi.org/10.7557/3.2683

Rowsell B & Maher PT (2017) Uniqueness as a draw for riding under the midnight sun. In: Latola K & Savola H (Eds.): The interconnected Arctic, pp. 221-229. Springer Polar Sciences, Springer International Publishing AG, Cham. https://doi.org/10.1007/978-3-319-57532-2

Runge CA, Daigle RM & Hausner VH (2020) Quantifying tourism booms and the increasing footprint in the Arctic with social media data. *PloS One* 15: e0227189. https://doi.org/10.1371/journal.pone.0227189

Ruohomäki K, Virtanen T, Kaitaniemi P, Tammaru T (1997) Old mountain birches at high altitudes are prone to outbreaks of *Epirrita autumnata* (Lepidoptera: Geometridae). *Environmental Entomology* 26:1096–1104. https://doi.org/10.1093/ee/26.5.1096

Saari R, Höckert E, Lüthje M, Kugapi O & Mazzullo N (2020) Cultural sensitivity in Sámi tourism: A systematic literature review in the Finnish context. *Finnish Journal of Tourism Research* 16: 93-110. https://doi.org/10.33351/mt.88061

Sae-Lim P, Kause A, Mulder HA & Olesen I (2017) Breeding and genetics symposium: Climate change and selective breeding in aquaculture. *Journal of Animal Science* 95; 1801-1812. https://doi.org/10.2527/jas.2016.1066

Salim E, Mabboux L, Ravanel L, Deline P & Gauchon C (2021) A history of tourism at the Mer de Glace: Adaptations of glacier tourism to glacier fluctuations since 1741. *Journal of Mountain Science* 18: 1974-1994. https://doi.org/10.1007/s11629-021-6723-5

Sambraus F, Fjelldal PG, Remø SC, Hevrøy EM, Nilsen TO, Thorsen A, Hansen TJ & Waagbø R (2017) Water temperature and dietary histidine affect cataract formation in Atlantic salmon (*Salmo salar* L.) diploid and triploid yearling smolt. *Journal of Fish Diseases* 40: 1195-1212. https://doi.org/10.1111/jfd.12594

Sandvik AD, Dalvin S, Skern-Mauritzen R & Skogen MD (2021) The effect of a warmer climate on the salmon lice infection pressure from Norwegian aquaculture. *ICES Journal of Marine Science* 78: 1849-1859. https://doi.org/10.1093/icesjms/fsab069

Sandvik SM & Odland A (2014) Changes in alpine snowbed-wetland vegetation over three decades in northern Norway. *Nordic Journal of Botany* 32: 377-384. https://doi.org/10.1111/j.1756-1051.2013.00249.x

Saville SM (2022) Valuing time: Tourism transitions in Svalbard. *Polar Record* 58: e11. https://doi.org/10.1017/S0032247422000055

Schiøtt S, Tejsner P & Rysgaard S (2022) Inuit and local knowledge on the marine ecosystem in Ilulissat Icefjord, Greenland. *Human Ecology* 50: 167-181. https://doi.org/10.1007/s10745-021-00277-2

Seneviratne SI, Zhang X (coordinating lead authors) et al. (14 lead authors & 56 contributing authors) (2021) Weather and climate extreme events in a changing climate. *In*: *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*, pp. 1513-1765. Cambridge University Press, Cambridge. https://doi.org/10.1017/9781009157896.013

Seppälä M & Rastas J (1980) Vegetation map of northernmost Finland with special reference to subarctic forest limits and natural hazards. *Fennia* 158: 41–61. https://fennia.journal.fi/article/view/9174

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Serreze MC & Barry RG (2011) Processes and impacts of Arctic amplification: a research synthesis. *Global and Planetary Change* 77: 85-96. https://doi.org/10.1016/j.gloplacha.2011.03.004

Serreze MC, Gustafson J, Barrett AP, Druckenmiller ML, Fox S, Voveris J, Stroeve J, Sheffield B, Forbes BC, Rasmus S, Laptander R, Brook M, Brubaker M, Temte J, McCrystall MR & Bartsch A (2021) Arctic rain on snow events: bridging observations to understand environmental and livelihood impacts. *Environmental Research Letters* 16: 105009. https://doi.org/10.1088/1748-9326/ac269b

Shaftel H (Ed.) (2022) *Global Climate Change. Vital Signs of the Planet. Sea Level*. NASA's Jet Propulsion Laboratory & California Institute of Technology. https://climate.nasa.gov/vital-signs/sea-level/

Shimmings P & Øien IJ (2015) Bestandsestimater for norske hekkefugler *Norsk ornitologisk forening Rapport* 2-2015. Norsk ornitologisk forening, Trondheim. 268 pp.

Shu Q, Wang Q, Årthun M, Wang S, Song Z, Zhang M & Qiao F (2022) Arctic Ocean Amplification in a warming climate in CMIP6 models. *Science Advances* 8: eabn9755. https://doi.org/10.1126/sciadv.abn9755

Sillmann J, Kharin VV, Zwiers FW, Zhang X & Bronaugh D (2013) Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. *Journal of Geophysical Research: Atmospheres* 118: 2473–2493. https://doi.org/10.1002/jgrd.50188

Simonsen CE, Madsen J, Tombre IM, Nabe-Nielsen J (2016) Is it worthwhile scaring geese to alleviate damage to crops? – an experimental study. *Journal of Applied Ecology* 53: 916–924. https://doi.org/10.1111/1365-2664.12604

Simpson MJR, Nilsen JEØ, Ravndal OR, Breili K, Sande H, Kierulf HP, Steffen H, Jansen E, Carson M & Vestøl O (2015) Sea Level Change for Norway - Past and Present Observations and Projections to 2100. *Norwegian Centre for Climate Services Report* 1/2015, 156 pp. https://www.miljodirektoratet.no/globalassets/publikasjoner/M405/M405.pdf

Skagseth Ø, Furevik T., Ingvaldsen R., Loeng H., Mork K. A., Orvik K. A., & Ozhigin V., 2008: Volume and heat transports to the Arctic Ocean via the Norwegian and Barents Seas. Arctic–Subarctic Ocean Fluxes. *In*: Dickson R, Meincke J & Rhines (Eds): *Arctic-Subarctic Ocean Fluxes*, pp. 45–64. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6774-7_3

Skarin A, Sandström P, Dos Santos BBN, Alam M, & Adler S (2021) Renar, renskötsel och vindkraft: vinter-och barmarksbete. Naturvårdsverket Rapport 7011. 126 pp. https://www.naturvardsverket.se/om-oss/publikationer/7000/renar-renskotsel-och-vindkraft/

Skre O (1995) The effect of raised CO_2 and winter temperatures on growth and carbon balance in Norway spruce seedlings. *Ecosystems Research Report* (European Commission) 10: 171-180.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Skre O & Nes K (1996) Combined effects of elevated winter temperatures and CO_2 on Norway spruce seedlings. *Silva Fennica* 30: 135-143.

Solheim H & Venn K (2003) Red belts. Occurrences in Norway in 2002. *In*: Thomsen IM (Ed.): *Forest health problems in older forest stands*, pp. 58–64. Danish Centre for Forest, Copenhagen.

Solli PE (2014) Økt interesse for Arktis. *HHD* 2014: 13. Norwegian Institute of International Affairs, Oslo. https://www.nupi.no/publikasjoner/innsikt-og-kommentar/hvor-hender-det/hhd-2014/oekt-interesse-for-arktis

Solvang O (2022) *Frykter for drikkevannet: Storstilt aksjon for å frakte ut over 70 døde dyr etter skredulykke: - En ubehagelig jobb*. Nordlys, Tromsø. https://www.nordlys.no/frykter-for-drikkevannet-storstilt-aksjon-for-a-frakte-ut-over-70-dode-dyr-etter-skredulykke-en-ubehagelig-jobb/s/5-34-1599458

Søndergaard J & Mosbech A (2022) Mining pollution in Greenland, the lesson learned: a review of 50 years of environmental studies and monitoring. *Science of the Total Environment* 812: 152373. http://doi.org/10.1016/j.scitotenv.2021.152373

Song Y, Sass-Klaassen U, Sterck F, Goudzwaard L, Akhmetzyanov L & Poorter L (2021). Growth of 19 conifer species is highly sensitive to winter warming, spring frost and summer drought. *Annals of Botany* 128: 545–557. https://doi.org/10.1093/aob/mcab090

Sonne C, Langebæk R, Dietz R, Andersen-Ranberg E, Houser G, Hansen AJ, Sinding MHS, Olsen MT, Egevang C, Gilbert MTP & Meldgaard M (2018) Greenland sled dogs at risk of extinction. *Science* 360: 1080-1080. https://doi.org/10.1126/science.aat9578

Sonntag S & Fourcade Y (2022) Where will species on the move go? Insights from climate connectivity modelling across European terrestrial habitats. *Journal for Nature Conservation* 66: 126139. https://doi.org/10.1016/j.jnc.2022.126139

Soppela P, Nieminen M & Timisjärvi J (1986) Thermoregulation in reindeer. *Rangifer* 1: 273–278. https://doi.org/10.7557/2.6.2.659

Sorteberg A, Lawrence D, Dyrrdal AV, Mayer S & Engeland K (2018) Climatic changes in short duration extreme precipitation and rapid onset flooding − implications for design values. *NCCS report* 1/2018, 144 pp. https://www.met.no/kss/_/attachment/download/de0e8d57-236c-460b-8e94-23ce18274c1c:94752a62e18693c0ea185e9db24381d209c475af/exprecflood-final-report-nccs-signert.pdf

Staneva A & Burfield I (Eds) (2017). *European birds of conservation concern: populations, trends and national responsibilities*. BirdLife International, Cambridge, UK. https://www.birdlife.ch/sites/default/files/documents/European_Birds_of_Conservation_Concern.pdf

Stark S, Ylänne H & Kumpula J (2021) Recent changes in mountain birch forest structure and understory vegetation depend on the seasonal timing of reindeer grazing. *Journal of Applied Ecology* 58: 941-952. https://doi.org/10.1111/1365-2664.13847

Statham S, Ford J, Berrang-Ford L, Lardeau MP, Gough W & Siewierski R (2015) Anomalous climatic conditions during winter 2010-2011 and vulnerability of the traditional Inuit food system in Iqaluit, Nunavut. *Polar Record* 51: 301-317. https://doi.org/10.1017/S0032247414000151

Statistics Norway (2022) *Holdings, agricultural area and livestock* [time series]. https://www.ssb.no/jord-skog-jakt-og-fiskeri/jordbruk/statistikk/gardsbruk-jordbruksareal-og-husdyr

Steiger R, Knowles N, Pöll K & Rutty M (2022) Impacts of climate change on mountain tourism: a review, *Journal of Sustainable Tourism*, early view. https://doi.org/10.1080/09669582.2022.2112204

Steingrund P (2019) Hví er toskurin á Føroyabanka ikki komin fyri seg? *Sjóvarmál* 2019: 10-13. Havstova (Faroe Marine Research Institute), Tórshavn. https://hav.fo/PDF/Ritgerdir/2019/Sjovarmal2019.pdf

Stempniewicz L, Kulaszewicz I & Aars J (2021) Yes, they can: polar bears *Ursus maritimus* successfully hunt Svalbard reindeer *Rangifer tarandus platyrhynchus*. *Polar Biology* 44: 2199–2206. https://doi.org/10.1007/s00300-021-02954-w

Stensen K, Krunegård A, Rasmusson K & Matti B (2019) Sveriges vattentillgång utifrån perspektivet vattenbrist och torka: Delrapport 1 i regeringsuppdrag om åtgärder för att motverka vattenbrist i ytvattentäkter. *SMHI Hydrologi* 120, 46 pp. SMHI, Stockholm. http://urn.kb.se/resolve?urn=urn:nbn:se:smhi:diva-5434

Stewart WS & Bannister P (1973) Dark respiration rates in *Vaccinium* spp. in relation to altitude. *Flora* 163: 415-421.

Stewart-Sinclair PJ, Last KS, Payne BL & Wilding TA (2020) A global assessment of the vulnerability of shellfish aquaculture to climate change and ocean acidification. *Ecology and Evolution* 10: 3518-3534. https://doi.org/10.1002/ece3.6149

Stigum VM, Jaarsma RI, Sprong H, Rolandsen CM & Mysterdu A (2019) Infection prevalence and ecotypes of *Anaplasma phagocytophilum* in moose *Alces alces*, red deer *Cervus elaphus*, roe deer *Capreolus capreolus* and *Ixodes ricinus* ticks from Norway. *Parasites & Vectors* 12: 1. https://doi.org/10.1186/s13071-018-3256-z

Stokke BG, Dale S, Jacobsen KO, Lislevand T, Solvang R & Strøm H (2021a) Fugler Aves - Norge. *In*: Artsdatabanken: *Norsk rødliste for arter 2021*. Artsdatabanken, Trondheim. https://artsdatabanken.no/rodlisteforarter2021/Artsgruppene/fugler

Stokke BG, Dale S, Jacobsen KO, Lislevand T, Solvang R & Strøm H (2021b) Fugler: Vurdering av ismåke *Pagophila eburnea* for Svalbard. *Norsk rødliste for arter 2021*. Artsdatabanken, Trondheim. https://www.artsdatabanken.no/lister/rodlisteforarter/2021/31848

Sturm M, Schimel J, Michaelson G, Welker JM, Oberbauer SF, Liston GE, Fahnestock J & Romanovsky VE (2005) Winter biological processes could help convert Arctic tundra to shrubland. *BioScience* 55: 17–26. https://doi.org/10.1641/0006-3568(2005)055[0017:WBPCHC]2.0.CO;2

Sulikowska A & Wypych A (2020) How unusual were June 2019 temperatures in the context of European climatology? *Atmosphere* 11: 697. https://doi.org/10.3390/atmos11070697

Svensson J, Andersson J, Sandström P, Mikusińsk, G & Jonsson BG (2019) Landscape trajectory of natural boreal forest loss as an impediment to green infrastructure. *Conservation Biology* 33: 152–163. https://doi.org/10.1111/cobi.13148

Svensson J, Bubnicki JW, Jonsson BG, Andersson J, & Mikusiński G (2020) Conservation significance of intact forest landscapes in the Scandinavian mountains green belt. *Landscape Ecology* 35: 2113–2131. https://doi.org/10.1007/s10980-020-01088-4

Svensson J, Bubnicki JW, Angelstam P, Mikusiński G & Jonsson BG (2022) Spared, shared and lost – routes for maintaining the Scandinavian Mountain foothill intact forest landscapes. *Regional Environmental Change* 22: 31 https://doi.org/10.1007/s10113-022-01881-8

Swann AL, Fung IY, Levis S, Bonan GB & Doney SC (2010) Changes in Arctic vegetation amplify high-latitude warming through the greenhouse effect. *Proceedings of the National Academy of Sciences of the United States of America* 107: 1295-1300. https://doi.org/10.1073/pnas.0913846107

Swedish Meteorological and Hydrological Institute (2022a) *Mätserier – Dataserier med normalvärden 1991-2020, 1961-1990*. https://www.smhi.se/data/meteorologi/nederbord

Swedish Meteorological and Hydrological Institute (2022b) *Klimatindikator – antal dagar med snötäcke*. https://www.smhi.se/klimat/klimatet-da-och-nu/klimatindikatorer/klimatindikator-antal-dagar-med-snotacke-1.91081

Swedish Meteorological and Hydrological Institute (2022c) *Ladda ner meteorologiska observationer- Abisko*. https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer/#param=snowDepth,stations=all,stationid=188800

Syse OB (1979) Finnmark i vær og vind. *In*: Hirsti R (Ed.): *Bygd og by i Norge - Finnmark*, pp. 67-78. Gyldendal, Oslo.

Talleklint L & Jaenson TG (1998) Increasing geographical distribution and density of *Ixodes ricinus* (Acari: Ixodidae) in central and northern Sweden. *Journal of Medical Entomology* 35:521–526. https://doi.org/10.1093/jmedent/35.4.521

Taveirne M, Ekemar L, Sánchez BG, Axelsson J & Zhang Q (2021) Mass balance sensitivity and future projections of Rabots Glaciär, Sweden. *Climate* 9: 126. https://doi.org/10.3390/cli9080126

Tenow O, Nilssen AC, Holmgren B, Elverum F (1999) An insect (*Argyresthia retinella*, Lep., Yponomeutidae) outbreak in northern birch forests, released by climatic changes? Journal of Applied Ecology 36: 111–122. https://doi:10.1046/j.1365-2664.1999.00385.x

The IMBIE Team (2020) Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature* 579: 233-239. https://doi.org/10.1038/s41586-019-1855-2

Thiault L, Mora C, Cinner JE, Cheung WW, Graham NA, Januchowski-Hartley FA, Mouillot D, Sumaila UR & Claudet J (2019) Escaping the perfect storm of simultaneous climate change impacts on agriculture and marine fisheries. *Science Advances* 5: eaaw9976. https://doi.org/10.1126/sciadv.aaw9976

Thoman R, Druckenmiller ML & Moon T (chapter eds.) (2022) The Arctic. *In*: State of the Climate in 2021 (Eds. Blunden J & Boyer T). *Bulletin of the American Meteorological Society* 103 (8): S257-S306. https://doi.org/10.1175/BAMS-D-22-0082.1

Thomas CD (2010) Climate, climate change and range boundaries. *Diversity and Distributions* 16: 488-495. https://doi.org/10.1111/j.1472-4642.2010.00642.x

Thuestad AE, Tømmervik H & Solbø SA (2015) Assessing the impact of human activity on cultural heritage in Svalbard: a remote sensing study of London. *The Polar Journal* 5: 428-445. https://doi.org/10.1080/2154896X.2015.1068536

Thyholdt SB (2014) The importance of temperature in farmed salmon growth: regional growth functions for Norwegian farmed salmon. *Aquaculture Economics & Management* 18: 189-204. https://doi.org/10.1080/13657305.2014.903310

Timmermans ML & Labe Z (2021) Sea Surface Temperature. *In*: *Arctic Report Card 2021* (Eds. Moon TA, Drucknemiller ML & Thoman RL). https://doi.org/10.25923/2y8r-0e49

Tombre IM, Oudman T, Shimmings P, Griffin L & Prop J (2019) Northward range expansion in spring-staging barnacle geese is a response to climate change and population growth, mediated by individual experience. *Global Change Biology* 25: 3680–3693. https://doi.org/10.1111/gcb.14793

Tømmervik H, Johansen B, Tombre I, Thannheiser D, Høgda KA, Gare E & Wielgolaski FE (2004) Vegetation changes in the Nordic mountain birch forest: the influence of grazing and climate change. *Arctic, Antarctic and Alpine Research* 36: 323–332. https://doi.org/10.1657/1523-0430(2004)036[0323:VCITNM]2.0.CO;2

Tømmervik H, Bjerke JW, Park T, Hanssen F & Myneni R (2019) Legacies of historical exploitation of natural resources are more important than summer warming for recent biomass increases in a boreal-arctic transition region. *Ecosystems* 22: 1512–1529. https://doi.org/10.1007/s10021-019-00352-2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Treharne R, Bjerke JW, Tømmervik H, Stendardi L & Phoenix GK (2019) Arctic browning: impacts of extreme climatic events on dwarf shrub heathland ecosystem CO_2 fluxes. *Global Change Biology* 25: 489–503. https://doi.org/10.1111/gcb.14500

Treharne R, Bjerke JW, Tømmervik H & Phoenix GK (2020) Development of new metrics to assess and quantify climatic drivers of extreme event driven Arctic browning. *Remote Sensing of Environment* 243: 111749. https://doi.org/10.1016/j.rse.2020.111749

Tryland M, Nymo IH, Sánchez Romano J, Mørk T, Klein J & Rockström U (2019) Infectious disease outbreak associated with supplementary feeding of semi-domesticated reindeer. *Frontiers in Veterinary Science* 6: 126. https://doi.org/10.3389/fvets.2019.00126

Tuhkanen S (1984) A circumboreal system of climatic-phytogeographical regions. *Acta Botanica Fennica* 127: 1-50 + App.

Tuhkanen S (1987) The phytogeographical position of the Faeroe Islands and their ecoclimatic correspondences on the other continents: Problems associated with highly oceanic areas. *Annales Botanici Fennici* 24: 111-135.

Turunen M, Soppela P, Kinnunen H, Sutinen M-L & Martz F (2009) Does climate change influence the availability and quality of reindeer forage plants? *Polar Biology* 32: 813–832. https://doi.org/10.1007/s00300-009-0609-2

Turunen M & Vuojala-Magga T (2014) Past and present winter feeding of reindeer in Finland: herders' adaptive learning of feeding practices. *Arctic* 67: 173–188. https://doi.org/10.14430/arctic4385

Turunen MT, Rasmus S, Bavay M, Ruosteenoja K & Heiskanen J (2016) Coping with difficult weather and snow conditions: reindeer herders' views on climate change impacts and coping strategies. *Climate Risk Management* 11: 15-36. https://doi.org/10.1016/j.crm.2016.01.002

Turunen MT, Rasmus S, Järvenpää J & Kivinen S (2020) Relations between forestry and reindeer husbandry in northern Finland – Perspectives of science and practice. *Forest Ecology and Management* 457: 117677. https://doi.org/10.1016/j.foreco.2019.117677

Tveraa T, Stien A & Langeland K (2016) Oppdatering av tallgrunnlaget for beregning av rovviltskadeerstatning på tamrein. *NINA Rapport* 1248, 28 pp. Norwegian Institute for Nature Research, Trondheim. http://hdl.handle.net/11250/2387573

Tveraa T, Stien A, Langeland K, Stien J & Tillman AM (2022) Kalvetilgang relatert til reintetthet, snøforhold, vårtidspunkt og planteproduksjon. *NINA Rapport* 2037, 34 pp. Norwegian Institute for Nature Research, Trondheim. https://hdl.handle.net/11250/3016175

Ustaoglu E & Collier MJ (2018) Farmland abandonment in Europe: an overview of drivers, consequences, and assessment of the sustainability implications. *Environmental Reviews* 26: 396-416. https://doi.org/10.1139/er-2018-0001

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

van der Wal R & Stien A (2014) High-arctic plants like it hot: a long-term investigation of between-year variability in plant biomass. Ecology 95: 3414-3427. https://doi.org/10.1890/14-0533.1

Vejen F, Vedel H & Scharling M (2021) Korrektion af observeret nedbør i Danmark. *DMI-rapport* 21-39, 19 pp. The Danish Meteorological Institute. https://www.dmi.dk/fileadmin/Rapporter/2021/DMI_21-39_-_Korrektion_af_observeret_nedboer_i_Danmark.pdf

Venäläinen A, Lehtonen I, Laapas M, Ruosteenoja K, Tikkanen OP, Viiri H, Ikonen VP & Peltola H (2020) Climate change induces multiple risks to boreal forests and forestry in Finland: A literature review. *Global Change Biology* 26: 4178–4196. https://doi.org/10.1111/gcb.15183

Vickers H, Malnes E, van Pelt WJJ, Pohjola VA, Killie MA, Saloranta T, Karlsen SR (2021) A compilation of snow cover datasets for Svalbard: a multi-sensor, multi-model study. *Remote Sensing* 13: 2002. https://doi.org/10.3390/rs13102002

Viinikka P (2022) *The highly endangered arctic fox managed to nest in Finland for the first time in over 25 years*. Yle, Helsinki. https://yle.fi/uutiset/3-12588238

Viiri H, Viitanen J, Mutanen A & Leppänen J (2019) Metsätuhot vaikuttavat Euroopan puumarkkinoihin – Suomessa vaikutukset toistaiseksi vähäisiä [Forest damage affects the European timber market – the effects in Finland are so far minor]. *Metsätieteen aikakauskirja* 2019: 10200. https://doi.org/10.14214/ma.10200

Vikhamar-Schuler D, Hanssen-Bauer I, Schuler TV, Mathiesen SD & Lehning M (2013) Use of a multilayer snow model to assess grazing conditions for reindeer. *Annals of Glaciology* 54: 214-226. https://doi.org/10.3189/2013AoG62A306

Vikhamar-Schuler D, Isaksen K, Haugen JE, Tømmervik H, Łuks B, Schuler TV & Bjerke JW (2016) Changes in winter warming events in the Nordic Arctic Region. *Journal of Climate* 29: 6223–6244, https://doi.org/10.1175/JCLI-D-15-0763.1

Vindstad OPL, Jepsen JU, Molvig H & Ims RA (2022) A pioneering pest: the winter moth (*Operophtera brumata*) is expanding its outbreak range into Low Arctic shrub tundra. *Arctic Science*. https://doi.org/10.1139/as-2021-0027

Virtanen T, Neuvonen S, Nikula A, Varama M & Niemelä P (1996) Climate change and the risks of *Neodiprion sertifer* outbreaks on Scots pine. *Silva Fennica* 30: 169-177. http://hdl.handle.net/1975/9229

Virtanen T, Neuvonen S & Nikula A (1998) Modelling topoclimatic patterns of egg mortality of *Epirrita autumnata* (Lepidoptera: Geometridae) with a geographical information system: predictions for current climate and warmer climate scenarios. *Journal of Applied Ecology* 35: 311-322. https://doi.org/10.1046/j.1365-2664.1998.00299.x

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869580.

Vollset KW, Lennox RJ, Davidsen JG, Eldøy SH, Isaksen TE, Madhun A, Karlsson S & Miller KM (2021) Wild salmonids are running the gauntlet of pathogens and climate as fish farms expand northwards. *ICES Journal of Marine Science* 78: 388-401. https://doi.org/10.1093/icesjms/fsaa138

Vormoor K, Lawrence D, Schlichting L, Wilson D & Wong WK (2016) Evidence for changes in the magnitude and frequency of observed rainfall vs. snowmelt driven floods in Norway. *Journal of Hydrology* 538: 33-48. https://doi.org/10.1016/j.jhydrol.2016.03.066

Vuojala-Magga T, Turunen M, Ryyppö T & Tennberg M (2011) Resonance strategies of Sami reindeer herders in northernmost Finland during climatically extreme years. *Arctic* 64: 227–241.

Wade NM, Clark TD, Maynard BT, Atherton S, Wilkinson RJ, Smullen RP & Taylor RS (2019) Effects of an unprecedented summer heatwave on the growth performance, flesh colour and plasma biochemistry of marine cage-farmed Atlantic salmon (*Salmo salar*). *Journal of Thermal Biology* 80: 64-74. https://doi.org/10.1016/j.jtherbio.2018.12.021

Walker DA, Daniëls FJA, Matveyeva NV, Šibík J, Walker MD, Breen AL, Druckenmiller LA, Raynolds MK, Bültmann H, Hennekens S, Buchhorn M, Epstein HE, Ermokhina K, Fosaa AM, Heidmarsson S, Heim B, Jónsdóttir IS, Koroleva N, Lévesque E, MacKenzie WH, Henry GHR, Nilsen L, Peet R, Razzhivin V, Talbot SS, Telyatnikov M, Thannheiser D, Webber PJ & Wirth LM (2018) Circumpolar Arctic Vegetation Classification. *Phytocoenologia* 48: 181-201. https://doi.org/10.1127/phyto/2017/0192

Walsh JE (2021) Arctic climate change, variability and extremes. *In*: Yang D & Kane DL (Eds.): *Arctic Hydrology, Permafrost and Ecosystems*, pp. 3-24. Springer Nature Switzerland, Cham.

Walsh JE, Ballinger TJ, Euskirchen ES, Hanna E, Mård J, Overland JE, Tangen H & Vihma T (2020) Extreme weather and climate events in northern areas: A review. *Earth-Science Reviews* 209: 103324. https://doi.org/10.1016/j.earscirev.2020.103324

Walsh JE, Ballinger TJ, Euskirchen ES, Hanna E, Mård J, Overland JE, Tangen H & Vihma T (2022) Extreme events and thresholds in the Arctic. *In*: AMAP Arctic Climate Change Update 2021: Key Trends and Impacts, pp. 51-74. Arctic Monitoring and Assessment Programme (AMAP), Tromsø.

Wang M, Benestad RE, Overland JE, Salvatori R, Salzano R, Shu Q, Sigmond M, Vitale V, Walsh J & Wang S (2022) Model assessment and future of the Arctic. *In*: AMAP Arctic Climate Change Update 2021: Key Trends and Impacts, pp. 31-49. Arctic Monitoring and Assessment Programme (AMAP), Tromsø.

Wehn S, Pedersen B & Hanssen SK (2011) A comparison of influences of cattle, goat, sheep and reindeer on vegetation changes in mountain cultural landscapes in Norway. *Landscape and Urban Planning* 102: 177-187. https://doi.org/10.1016/j.landurbplan.2011.04.003

Weijers S (2022) Declining temperature and increasing moisture sensitivity of shrub growth in the low-Arctic erect dwarf-shrub tundra of western Greenland. *Authorea* (Feb 4, 2022). https://10.22541/au.164395278.85793360/v1

Weladji RB, Holand Ø & Almøy T (2003) Use of climatic data to assess the effect of insect harassment on the autumn weight of reindeer (*Rangifer tarandus*) calves. *Journal of Zoology* 260: 79–85. https://doi.org/10.1017/S0952836903003510

Wenger M (2022) *Billionaire invests into mining project in Greenland for e-transportation*. Polar Journal, Zürich. https://polarjournal.ch/en/2022/08/11/billionaire-group-invests-into-mining-project-in-greenland-for-e-transportation/

Wernick IK, Ciais P, Fridman J, Högberg P, Korhonen KT, Nordin A & Kauppi PE (2021) Quantifying forest change in the European Union. *Nature* 592: E13–E14. https://doi.org/10.1038/s41586-021-03293-w

Westling A, Toräng P, Jacobsson A, Haldin M & Naeslund M (Eds) (2020) *Sveriges arter och naturtyper i EU:s art- och habitatdirektiv – resultat från rapportering 2019 till EU av bevarandestatus 2013-2018*. Naturvårdsverket, Stockholm. https://www.naturvardsverket.se/om-oss/publikationer/6900/sveriges-arter-och-naturtyper-i-eus-art--och-habitatdirektiv

Wilhelms H, Klausen DH, Saijets JA & Hætta ÁM (2022) *70 reinsdyr tatt av snøskred: – Hos noen stakk bare føttene opp*. Norwegian Broadcasting Corporation. https://www.nrk.no/tromsogfinnmark/70-reinsdyr-tatt-av-snoskred-i-nord-troms_-_-en-dyretragedie-1.15855227

Williams CM, Henry HAL & Sinclair BJ (2015): Cold truths: How winter drives responses of terrestrial organisms to climate change. *Biological Reviews* 90: 214–235. https://doi.org/10.1111/brv.12105

Wilson RJ (2022) Northern wildlife feels the heat. *Nature Climate Change* 12: 506–507. https://doi.org/10.1038/s41558-022-01378-6

Wolken GJ, Liljedahl AK, Brubaker M, Coe JA, Fiske G, Christiansen HH, Jacquemart M, Jones BM, Kääb A, Løvholt F, Natali S, Rudy ACA & Streletskiy D (2022) Glacier and permafrost hazards. *NOAA Arctic Report Card* 2021: 93-101. https://doi.org/10.25923/v40r-0956

Woollings T, Barriopedro D, Methven J, Son SW, Martisu O, Harvey B, Sillmann J, Lupo AR & Seneviratne S (2018) Blocking and its response to climate change. *Current Climate Change Reports* 4: 287–300. https://doi.org/10.1007/s40641-018-0108-z

Xu L, Myneni R, Chapin III F, Callaghan TV, Pinzon JE, Tucker CJ, Zhu Z, Bi J, Ciais P, Tømmervik H, Euskirchen ES, Forbes BC, Piao SL, Anderson BT, Ganguly S, Nemani RR, Goetz SJ, Beck PSA, Bunn AG, Cao C & Stroeve JC (2013) Temperature and vegetation seasonality diminishment over northern lands. *Nature Climate Change* 3: 581–586. https://doi.org/10.1038/nclimate1836

Xu X, Riley WJ, Koven CD, Jia G & Zhang X (2020) Earlier leaf-out warms air in the north. *Nature Climate Change* 10: 370-375. https://doi.org/10.1038/s41558-020-0713-4

Ye H, Yang D, Behrangi A, Stuefer SL, Pan X, Mekis E, Dibike Y & Walsh JE (2021) Precipitation characteristics and changes. *In*: Yang D & Kane DL (Eds.): *Arctic Hydrology, Permafrost and Ecosystems*, pp. 25-60. Springer Nature Switzerland, Cham.

You Q, Cai Z, Chen D, Ahrens B, Jiang Z, Wu F, Kang S, Zhang R, Wu T, Wang P, Li M, Zuo M, Gao Y, Zhai P & Zhang Y (2021) Warming amplification over the Arctic Pole and Third Pole: Trends, mechanisms and consequences. *Earth-Science Reviews* 217: 103625. https://doi.org/10.1016/j.earscirev.2021.103625

Yurkevich N, Fadeeva I, Shevko E, Yannikov A & Bortnikova S (2021) Modeling the process of thawing of tailings dam base soils by technological waters. *Applied Sciences* 11: 11089. https://doi.org/10.3390/app112311089

Zhou N, Hu X, Byskov I, Næss JS, Wu Q, Zhao W & Cherubini F (2021) Overview of recent land cover changes, forest harvest areas, and soil erosion trends in Nordic countries. *Geography and Sustainability* 2: 163-174. https://doi.org/10.1016/j.geosus.2021.07.001

Zhu Z, Piao S, Myneni R, Huang M, Zeng Z, Canadell JG, Ciais P, Sitch S, Friedlingstein P, Arneth A, Cao C, Cheng L, Kato E, Koven C, Li Y, Lian X, Liu Y, Liu R, Mao J, Pan Y, Peng S, Peñuelas J, Poulter B, Pugh TAM, Stocker BD, Viovy N, Wang X, Wang Y, Xiao Z, Yang H, Zaehle S & Zeng N (2016) Greening of the Earth and its drivers. *Nature Climate Change* 6: 791–795. https://doi.org/10.1038/nclimate3004

Zimmermann NE, Yoccoz NG, Edwards TC, Meier ES, Thuiller W, Guisan A, Schmatz DR & Pearman PB (2009). Climatic extremes improve predictions of spatial patterns of tree species. *Proceedings of the National Academy of Sciences of the United States of America* 106: 19723–19728. https://doi.org/10.1073/pnas.0901643106

Zinke L (2021) Storm surges and salt marshes. *Nature Reviews Earth & Environment* 2: 448. https://doi.org/10.1038/s43017-021-00196-2

Zona D, Lafleur PM, Hufkens K, Bailey B, Gioli B, Burba G, Goodrich JP., Liljedahl AK, Euskirchen ES, Watts JD, Farina M, Kimball JS, Heimann M, Göckede M, Pallandt M, Christensen TR, Mastepanov M, López-Blanco E, Jackowicz-Korczynski M, Dolman AJ, Marchesini LB, Commane R, Wofsy SC, Miller CE, Lipson DA, Hashemi J, Arndt KA, Kutzbach L, Holl D, Boike J, Wille C, Sachs T, Kalhori A, Song X, Xu X, Humphreys ER, Koven CD, Sonnentag O, Meyer G, Gosselin GH, Marsh P & Oechel WC (2022) Earlier snowmelt may lead to late season declines in plant productivity and carbon sequestration in Arctic tundra ecosystems. *Scientific Reports* 12: 3986. https://doi.org/10.1038/s41598-022-07561-1

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