

The missing pieces for better future predictions in subarctic ecosystems: A Torneträsk case study

Didac Pascual , Jonas Åkerman, Marina Becher, Terry V. Callaghan, Torben R. Christensen, Ellen Dorrepaal, Urban Emanuelsson, Reiner Giesler, Dan Hammarlund, Edward Hanna, Annika Hofgaard, Hongxiao Jin, Cecilia Johansson, Christer Jonasson, Jonatan Klaminder, Jan Karlsson, Erik Lundin, Anders Michelsen, David Olefeldt, Andreas Persson, Gareth K. Phoenix, Zofia Rączkowska, Riikka Rinnan, Lena Ström, Jing Tang, Ruth K. Varner, Philip Wookey, Margareta Johansson

Received: 8 June 2020 / Revised: 8 June 2020 / Accepted: 8 August 2020 / Published online: 13 September 2020

Abstract Arctic and subarctic ecosystems are experiencing substantial changes in hydrology, vegetation, permafrost conditions, and carbon cycling, in response to climatic change and other anthropogenic drivers, and these changes are likely to continue over this century. The total magnitude of these changes results from multiple interactions among these drivers. Field measurements can address the overall responses to different changing drivers, but are less capable of quantifying the interactions among them. Currently, a comprehensive assessment of the drivers of ecosystem changes, and the magnitude of their direct and indirect impacts on subarctic ecosystems, is missing. The Torneträsk area, in the Swedish subarctic, has an unrivalled history of environmental observation over 100 years, and is one of the most studied sites in the Arctic. In this study, we summarize and rank the drivers of ecosystem change in the Torneträsk area, and propose research priorities identified, by expert assessment, to improve predictions of ecosystem changes. The research priorities identified include understanding impacts on ecosystems brought on by altered frequency and intensity of winter warming events, evapotranspiration rates, rainfall, duration of snow cover and lake-ice, changed soil moisture, and droughts. This case study can help us understand the ongoing ecosystem changes occurring in the Torneträsk area, and contribute to improve predictions of future ecosystem changes at a larger scale. This understanding will provide the basis for the future

mitigation and adaptation plans needed in a changing climate.

Keywords Abiotic drivers · Arctic and subarctic · Biotic drivers · Ecosystem change · Research priorities

INTRODUCTION

Increasing greenhouse gas concentrations in the atmosphere have resulted in a general increase in Earth's surface temperature during the last decades (IPCC 2013). However, climate change has many facets, including changes in precipitation, snow regime, extreme weather, and biotic events, and these changes occur alongside other anthropogenic drivers, such as changes in land use and pollution. All these drivers interact and therefore it is very complex to predict the future of arctic ecosystems.

In the Arctic, the temperature increase is twice as fast as the global average (Cohen et al. 2014), mostly due to the reduced surface albedo, linked to the declining Arctic sea ice extent (Walsh 2014) and snow cover duration (Brown et al. 2017). This trend is likely to continue throughout the twenty-first century (Collins et al. 2013). Apart from the observed increase in air temperature, a general (although uneven) increase in precipitation, both in the form of rain (IPCC 2013), and in some areas snow (Park et al. 2012), has been observed in the Arctic region over recent decades, a trend that is also projected to continue throughout the twenty-first century (IPCC 2013). Given that arctic and subarctic ecosystems are strongly dependent on, and adapted to, specific climatic conditions, these ongoing and predicted climatic changes could impact their biotic (e.g.

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s13280-020-01381-1>) contains supplementary material, which is available to authorized users.

vegetation and the carbon cycle) and abiotic (e.g. permafrost, hydrology, and local climate) components.

In addition to the observed long-term changes in temperature and precipitation, the frequency and intensity of extreme events, such as fires, winter warming events, extreme rainfall, severe droughts and insect outbreaks, has also increased in the Arctic during recent decades (e.g. Soja et al. 2007; Kivinen et al. 2017). These short-lasting stochastic events have already caused abrupt impacts on arctic ecosystems (e.g. Phoenix and Bjerke 2016; Sokolov et al. 2016), which could grow under the predicted scenarios of more intense and frequent extreme events (e.g. Vikhamar-Schuler et al. 2016; Young et al. 2017).

However, climate change is not the only driver of ecosystem change in the arctic and subarctic areas (ACIA 2005). Rather, the observed changes result from the combined effect of climate change and other anthropogenic factors that are, in turn, highly dependent on governmental policies, such as reindeer herding, land use changes, and pollution. The total magnitude of the ecosystem changes results from the interactions between the different drivers. These changes could potentially have important implications for ecosystem services of vital importance for the local residents (provisioning services, such as food, freshwater or biomass) and for the global population (regulatory services, such as global carbon and energy budgets). Thus, a better understanding of potential future ecosystem changes is paramount for defining climate change mitigation goals and adaptation strategies.

In order to make predictions of the future dynamics of ecosystems, data gathered through monitoring of specific parameters, and the process understanding gained through manipulation experiments, are combined in ecosystem models (e.g. LPJ-GUESS, Smith et al. 2014). These predictions have been improved over the last decades as more data have become available and more advanced ecosystem models have been developed (e.g. Tang et al. 2015.). Nevertheless, these predictions still hold large uncertainties at all spatial and temporal scales, arising mostly from insufficient data, lack of process understanding, and/or model limitations in representing these interacting and other processes. For example, modelled predictions of tree-line movement on subarctic plains have been over-estimated by up to > 1000 times (e.g. Van Bogaert et al. 2011).

Field measurements mostly address overall responses to some changing drivers, rather than the effect of the different interactions between them. Currently, a comprehensive assessment of the drivers (including their direct and indirect effects) of different changes and the magnitude of their impact on subarctic ecosystems is missing.

The Torneträsk area, in the Swedish subarctic, has an unrivalled history of environmental observation spanning

over a century (Callaghan et al. 2010; Jonasson et al. 2012), and syntheses of ecosystem changes (e.g. Callaghan et al. 2013). Studies from the Torneträsk area feature in some 12% of all published papers and 19% of all study citations across the Arctic (Metcalf et al. 2018), excluding internal Russian studies. In the present study, we aim, based on expert opinion, to (i) summarize and rank, in perceived importance, the drivers (including their direct and indirect impacts) of ecosystem change in the Torneträsk area, and to (ii) propose research priorities that are needed to improve future predictions of ecosystem change in the study area and potentially in other arctic ecosystems. The relatively small size of the Torneträsk area, its great biological and geomorphological diversity, and its unique datasets, present a well-curated microcosm of the Subarctic. Its rapidly-transforming ecosystems can underpin an improved understanding of the ongoing processes and future ecosystem changes at a larger circumpolar scale. This understanding, in turn, will provide the basis for future mitigation and adaptation plans needed in a changing climate.

METHODOLOGY

Study area

The study area includes the northwest part of the Lake Torneträsk catchment, and was delineated to include the climatic, altitudinal, and vegetation gradients occurring in the area (Fig. 1). The region contains highly varied topography, with altitudes ranging between 342 and > 1900 m a.s.l. (Andersson et al. 1996). The climate presents a strong northwest-southeast oceanic-continental gradient, resulting in significant eastward declines in precipitation and winter temperature, caused by increasing distance from the Atlantic Ocean and the strong rain shadow effect caused by the Scandes Mountains. At the Abisko Scientific Research Station (ANS; 385 m a.s.l.), mean annual air temperature (MAAT) increased by 2.5 °C over the period 1913–2006 (Callaghan et al. 2010), and is currently 0.4 °C (ANS 2020). Meteorological data from Abisko Observatory, annual mean 2010–01–01–2019–12–31). Total annual precipitation ranges from > 1000 mm in the north-western areas to ~ 300 mm in the central and southeastern parts of the study area. At the ANS, the mean annual precipitation for the period 2010–2019 was 357 mm, 19% higher than the 301 mm corresponding to the period 1961–1990 (ANS 2020). Meteorological data from Abisko Observatory, annual mean 2010–01–01–2019–12–31).

Vegetation in the area varies with altitude, and is also dependent on hydrology. In the lowlands, birch (*Betula*

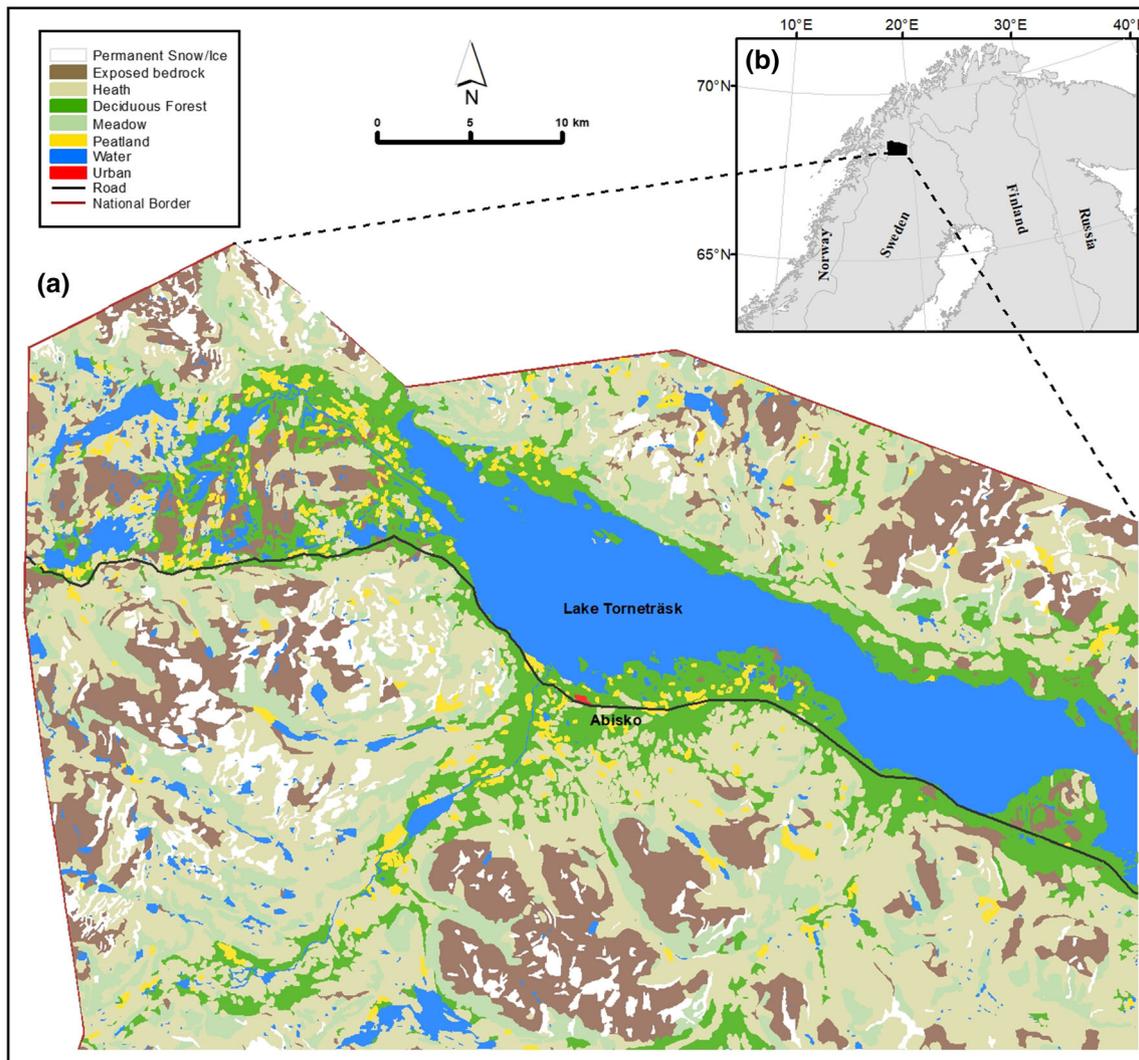


Fig. 1 **a** The study area in northernmost Sweden, including dominant land cover classes derived from Lantmäteriet (2006), Sweden. **b** Geographical overview of the study area. Source: Esri; Michael Bauer Research GmbH

pubescens var *pumila* L.)-dominated deciduous forests alternate with wetland areas composed of shrubs (e.g. *Vaccinium uliginosum* L.), mosses (e.g. *Sphagnum fuscum* (Schimp.)), lichens (e.g. *Cetraria cucullata*) and graminoids (e.g. *Eriophorum vaginatum* L.) (Johansson et al. 2013), which are expanding in areas of permafrost degradation (e.g. Christensen et al. 2004). Birch-dominated forests occur below an approximate altitudinal limit of 600 and 800 m a.s.l. in the western and eastern parts of the Torneträsk area, respectively (Wielgolaski et al. 2005), and have expanded their altitudinal and latitudinal ranges during recent decades (Callaghan et al. 2013, and references therein). Above the tree-line, the vegetation is mostly composed of dwarf shrub heathland (e.g. *Empetrum hermaphroditum*, and *Vaccinium* species), meadows dominated by sedges, herbs, and graminoids (Sundqvist et al. 2013), and snowbed communities (Björk et al. 2007),

which, except for the latter, have increased in areal extent and species richness over the recent decades (e.g. Hedenås et al. 2012). Vegetation cover tends to disappear as elevation increases and where bedrock is exposed or small sized glaciers occur.

According to Brown et al. (1998), the area is characterized by the presence of discontinuous permafrost, although the area is now more characteristic of the sporadic permafrost zone (Johansson et al. 2011a, b). Permafrost occurs in the mountains above ~ 850 m a.s.l. on the northeast and east-facing slopes, and above 1100 m a.s.l. on the south-facing slopes (Ridefelt et al. 2008). At lower elevations, permafrost sporadically occurs in mires with ombrotrophic peat mounds (Johansson et al. 2006).

Soils are mostly composed of till, colluvium, and glaciofluvial deposits. More calcareous bedrock promoting higher nitrogen availability is found in the north-western

parts of the study area and decreases towards the east, although some nutrient-rich areas are also found in the central part (Björk et al. 2007).

The fauna in the Abisko area is diverse and plays an important role in the ecosystem dynamics, with reindeer (*Rangifer tarandus*), moose (*Alces alces*), lemmings (*Lemmus lemmus*), voles (e.g. *Myodes rufocanus*) and some geometrid moth species (e.g. *Epirrita autumnata*) having a distinct impact on the vegetation dynamics of the area (Callaghan et al. 2013).

Literature review

Five ecosystem components were explored in this study: local climate (temperature and precipitation), permafrost, hydrology, vegetation, and the carbon cycle. Long and short-term field and laboratory studies, modelling papers, and synthesis of multiple studies conducted in the Torneträsk area, were examined to identify (1) drivers (and their direct and indirect effects) that are changing the ecosystem components above, and (2) the underlying processes, or causal pathways, by which a driver could affect a specific ecosystem component. A total of 30 drivers and over 700 processes were identified (see Appendix S1).

The expert assessment

Between May and August 2019, 27 leading scientists contributed to an Expert Assessment about ecosystem change in the Torneträsk area. The experts were selected based on their expertise in at least one of the five ecosystem components of interest, and on their previous work in the study area (for > 5 years, some up to > 50 years) (Appendix S3).

The Expert Assessment consisted of an online survey which was answered by each expert using the online platform surveygizmo (<https://www.surveygizmo.com/>). The methods employed in developing the survey were inspired from those designed by Sutherland et al. (2011), and were modified and adapted according to our objectives and needs.

The experts were asked to answer three questions for each of the 30 drivers explored (including both their direct and indirect impacts), and concerning the ecosystem component they had expertise in (Appendix S1). Question 1 asked them to rank (1–9) the importance of a given driver on the ecosystem component concerned, for the periods 2020–2040 (Question 1A) and 2040–2100 (Question 1B). Question 2 asked them to rank (1–9) how well studied are the potential future impacts of each driver on the ecosystem component concerned. Question 3 allowed the experts to provide self-reported expertise (1–5) for each particular

driver. The experts had the option to suggest important studies that they believe need to be conducted in the future. The participants were provided with the following material (see Appendix S1): (i) general instructions; (ii) the findings of the literature review, and (iii) a detailed example of how to answer the survey.

All responses belonging to the same group of experts were gathered and analysed together using the same methodology, which is described in detail in the supplementary material (Appendix S2). Responses for Question 1 (variable importance) were normalized on a 0–10 scale. The scores for Question 2 (variable awareness) were inverted in order to convert awareness into novelty, which is indicative of how new, or understudied, the ecosystem impacts of a given driver are. Subsequently, the novelty scores were normalized on a 0–10 scale. All responses for each variable (importance and novelty) were aggregated by averaging the normalized scores. In reporting results, responses with self-rated expertise of 1 (not familiar) were excluded. In this study, drivers presenting high importance (> 6) and high novelty (> 5) scores were considered research priorities.

RESULTS

In the Torneträsk region, 21 of the 30 drivers (including their direct and indirect effects) identified were ranked as the top ten most important drivers for at least one of the ecosystem components and study periods (Table 1). Air temperature was ranked as the most important driver for all ecosystem components and for both study periods, except for hydrology (where rainfall was top-ranked) and carbon cycle (where lake-ice duration was top-ranked for the period 2020–2040). Only air temperature, winter warming events, and snow cover were ranked in the top ten most important drivers for all the components and periods studied.

A total of 15 drivers were identified as research priorities for at least one of the ecosystem components and periods included in the study (Table 1). Of these, only rainfall, evapotranspiration, and winter warming events were ranked as research priorities for all the components elicited, for at least one study period. Furthermore, winter warming events was the only driver ranked as a research priority for all components and time periods.

A summary of the important future studies suggested by the different groups of experts is available in the Supplementary Material (Appendix S4). The experts' estimates of importance and novelty, for the top 10 most important drivers for each ecosystem component, are summarized below and in Appendix S3.

Table 1 Summary of the most important drivers (including their direct and indirect effects) (with mean importance estimates, on a 0–10 scale, calculated based on the experts' responses from all groups; $n = 5$), and research priorities (identified by number of expert groups, on a 0–5 scale)

Most important drivers (mean importance estimates across all groups)		Research priorities (identified by number of expert groups)	
2020–2040	2040–2100	2020–2040	2040–2100
Air temperature (8.5)	Air temperature (8.9)	Winter warming events (5)	Winter warming events (5)
Snow cover (7.8)	Snow cover (8.2)	Evapotranspiration (3)	Evapotranspiration (5)
Winter warming events (7.3)	Rainfall (8)	Rainfall (3)	Rainfall (4)
Rainfall (7)	Winter warming events (7.4)	Snow cover (3)	Snow cover (3)
Snow depth (6.8)	Evapotranspiration (6.8)	Lake-ice duration (3)	Lake-ice duration (3)
Evapotranspiration (6.5)	Soil moisture (6.7)	Soil moisture (3)	Soil moisture (3)
Soil moisture (6.4)	Snow depth (6.5)	Droughts (2)	Drought (3)
Lake-ice duration (6.2)	Snow-water equivalent (6.2)	Snow-water equivalent (2)	Snow-water equivalent (2)
Snow-water equivalent (6)	Lake-ice duration (5.9)	Snow depth (2)	Snow depth (2)
Plant productivity (5.7)	Droughts (5.6)	River discharge – groundwater flow (2)	River discharge—groundwater flow (1)
River discharge—groundwater flow (5.7)	River discharge—groundwater flow (5.4)	Extreme rainfall events (1)	Extreme rainfall events (1)
Cloud cover (5.6)	Cloud cover (5.3)	Air temperature (1)	Air temperature (1)
Extreme rainfall events (5.4)	Dissolved organic carbon (5.2)	Plant productivity (1)	Plant productivity (1)
Droughts (5.1)	Extreme rainfall events (5.1)	Cloud cover (1)	Cloud cover (0)
Insect outbreaks (4.7)	Insect outbreaks (4.7)	Insect outbreaks (0)	Insect outbreaks (1)
Active layer thickness (4.7)	Active layer thickness (4.2)		
Reindeer herding (4.4)	Insect population (4)		
Insect population (3.4)	Plant productivity (3.9)		
Rodents population (3.2)	Rodents population (3.4)		
Dissolved organic carbon (2.9)	Black carbon (3.3)		
Black carbon (2)	Reindeer herding (2.6)		

Local climate

The relative importance of four drivers (air temperature, winter warming events, lake-ice duration, and droughts) increased over time (Fig. 2a and Appendix S3). On the contrary, large decreases in relative importance were observed for rainfall, snow cover, cloud cover, and snow depth. The changes in the relative importance of these drivers over time predicted by the experts resulted in changes in their scores and relative positions in the ranking, excluding cloud cover and snow depth, and incorporating snow water equivalent and black carbon in the top ten list for the period 2040–2100.

The research priorities identified for the period 2020–2040 (Fig. 2b) were snow cover, cloud cover, lake-ice duration, winter warming events, rainfall, and evapotranspiration. For the period 2040–2100, snow cover, lake-ice duration, evapotranspiration, rainfall, and winter warming events, were still perceived as important topics for further studies, in addition to droughts (Fig. 2c).

Permafrost

The relative importance of all drivers decreased over time, except for rainfall, snow-water equivalent and evapotranspiration (Fig. 3a and Appendix S3). For the period 2040–2100, the top ten list of most important drivers excluded plant productivity, but included evapotranspiration.

For the period 2020–2040, snow water equivalent, droughts, soil moisture, river discharge and groundwater flow, winter warming events, and rainfall, were suggested as permafrost research priorities (Fig. 3b). All of these drivers were still perceived as priority research for the period 2040–2100, in addition to evapotranspiration (Fig. 3c).

Hydrology

Given the particularly high importance and novelty scores assigned to a large number of hydrological drivers, we

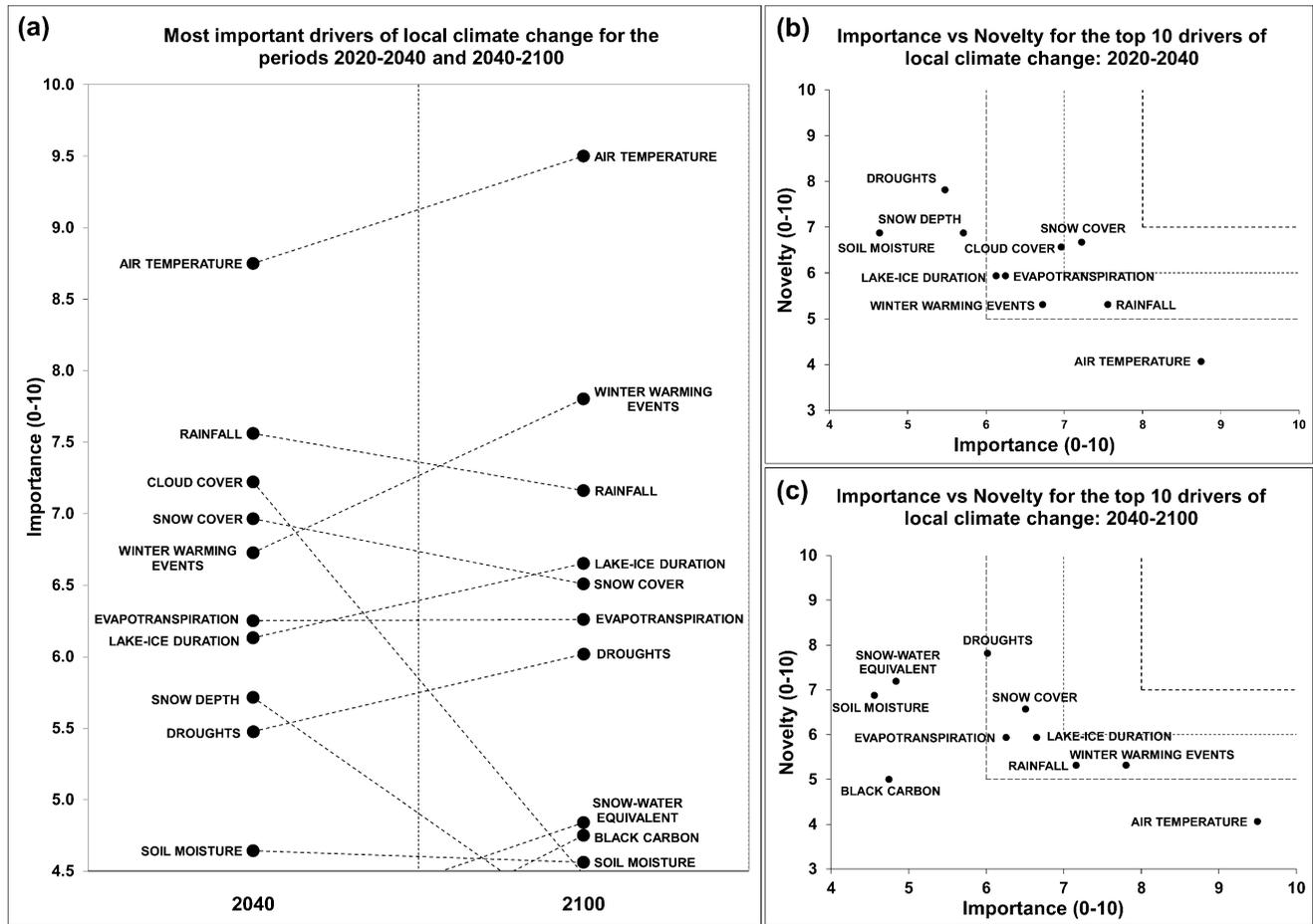


Fig. 2 a The ten most important drivers of local climate change for the periods 2020–2040 and 2040–2100. b, c Future research priorities identified through importance vs novelty for the most important drivers of local climate change, for the periods 2020–2040 and 2040–2100, respectively

retained drivers presenting a mean importance score > 7 in the top list of important drivers (Fig. 4a and Appendix S3). The relative importance of four drivers (rainfall, snow cover, winter warming events and droughts) increased over time. On the contrary, substantial decreases are visible in the relative importance of snow depth, snow-water equivalent, lake-ice duration, and soil moisture, in 2040–2100. These changes resulted in the exclusion of soil moisture and the addition of plant productivity in the top 11 list of important drivers for the period 2040–2100.

For the period 2020–040, winter warming events, extreme rainfall events, droughts, evapotranspiration, lake-ice duration, air temperature, and soil moisture, were identified as hydrology research priorities (Fig. 4b). Of these drivers, only soil moisture was no longer perceived as a research priority for the period 2040–2100. In addition, plant productivity was included as a research priority (Fig. 4c).

Vegetation

Substantial increases over time were observed in the relative importance of air temperature, rainfall, winter warming events, and soil moisture (Fig. 5a and Appendix S3). In contrast, decreases were observed in the relative importance of insect population, rodent populations, river discharge, and groundwater flow. These changes resulted in the exclusion of river discharge and groundwater flow, and the incorporation of soil moisture in the top 10 list for the period 2040–2100.

The vegetation research priorities identified for the near future (2020–2040) were evapotranspiration, river discharge and groundwater flow, winter warming events, and snow depth (Fig. 5b). With regard to the period 2040–2100, evapotranspiration, winter warming events, and snow depth, remained as research priorities, in addition to soil moisture (Fig. 5c).

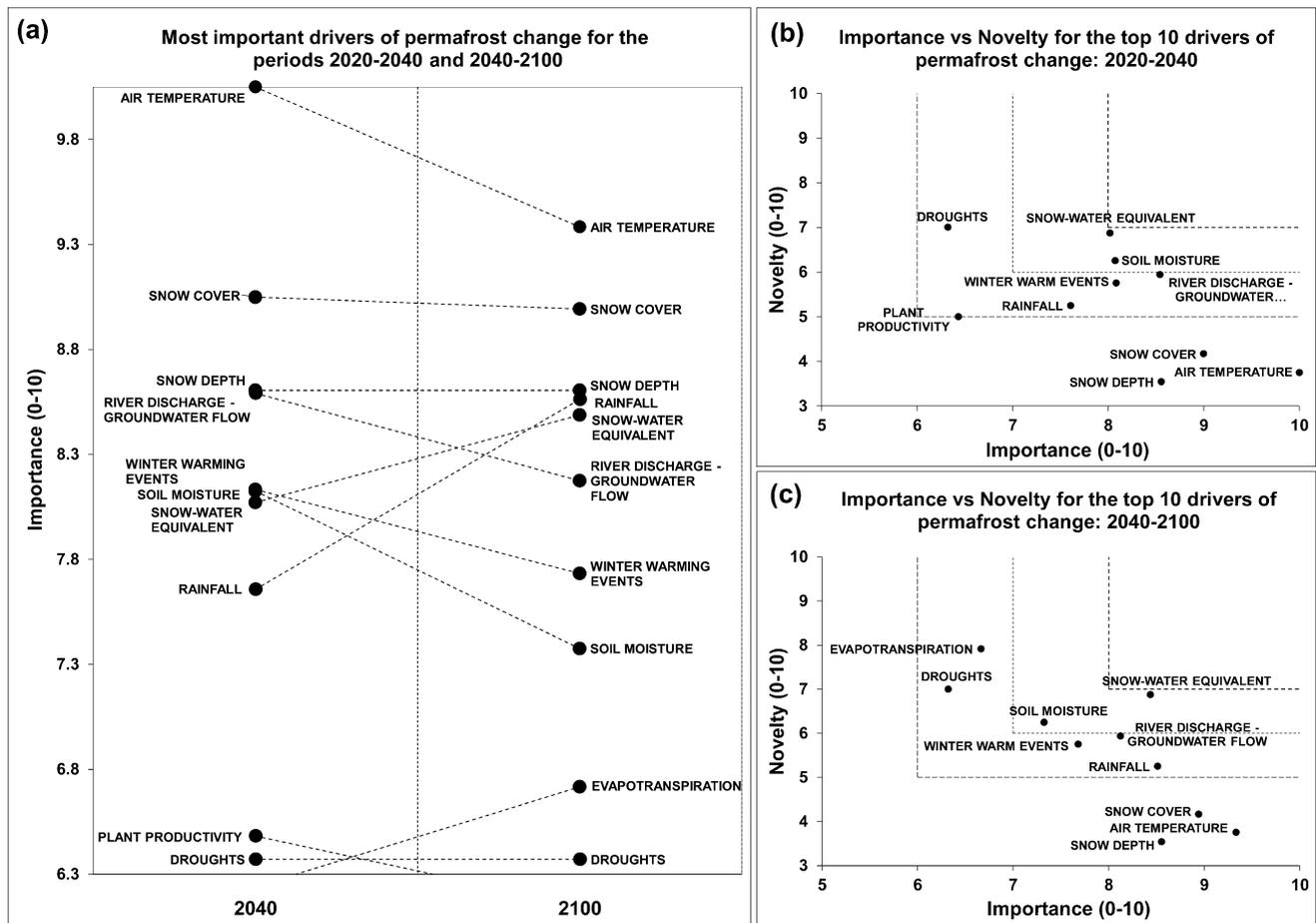


Fig. 3 a The ten most important drivers of permafrost change for the periods 2020–2040 and 2040–2100. b, c Future research priorities identified through importance vs novelty for the most important drivers of permafrost change for the periods 2020–2040 and 2040–2100, respectively

Carbon cycle

The mean estimates from all expert responses indicate a projected strong increase over time in the relative importance of all the top ten most important drivers, with the exception of active layer thickness, which was excluded from the top ten list for the period 2040–2100 (Fig. 6a and Appendix S3).

The drivers identified by the experts as research priorities for the period 2020–2040 are lake-ice duration, winter warming events, snow cover, and soil moisture (Fig. 6b). These four drivers, together with rainfall, insect outbreaks, and evapotranspiration, represent the carbon cycle research priorities for the period 2040–2100 (Fig. 6c).

RESEARCH PRIORITIES AND WAYS FORWARD

In this study, the drivers (including their direct and indirect impacts) of ecosystem change in the Torneträsk area were

ranked, and future research priorities were identified. In this section, we will focus on the top research priorities identified by at least three groups of experts (out of five; on local climate, permafrost, hydrology, vegetation, and the carbon cycle). These research priorities are deemed to be the most important elements that require particular focus to underpin more robust future predictions of ecosystem changes in the study area. We particularly highlight important interactions among the drivers that have hitherto been neglected in the area.

We propose further studies on each of these drivers according to the 3 M concept (Johansson et al. 2012), using monitoring (in-situ and remote sensing; including a better collaboration with the local and Indigenous Peoples to increase the observational power), manipulation experiments (to simulate changes in the current dynamics of the drivers and evaluate the resulting impacts on ecosystems), and finally modelling (to upscale the local findings). This has been further developed into a 4 M concept to recognize the end point of “management” (Callaghan *pers.comm*).

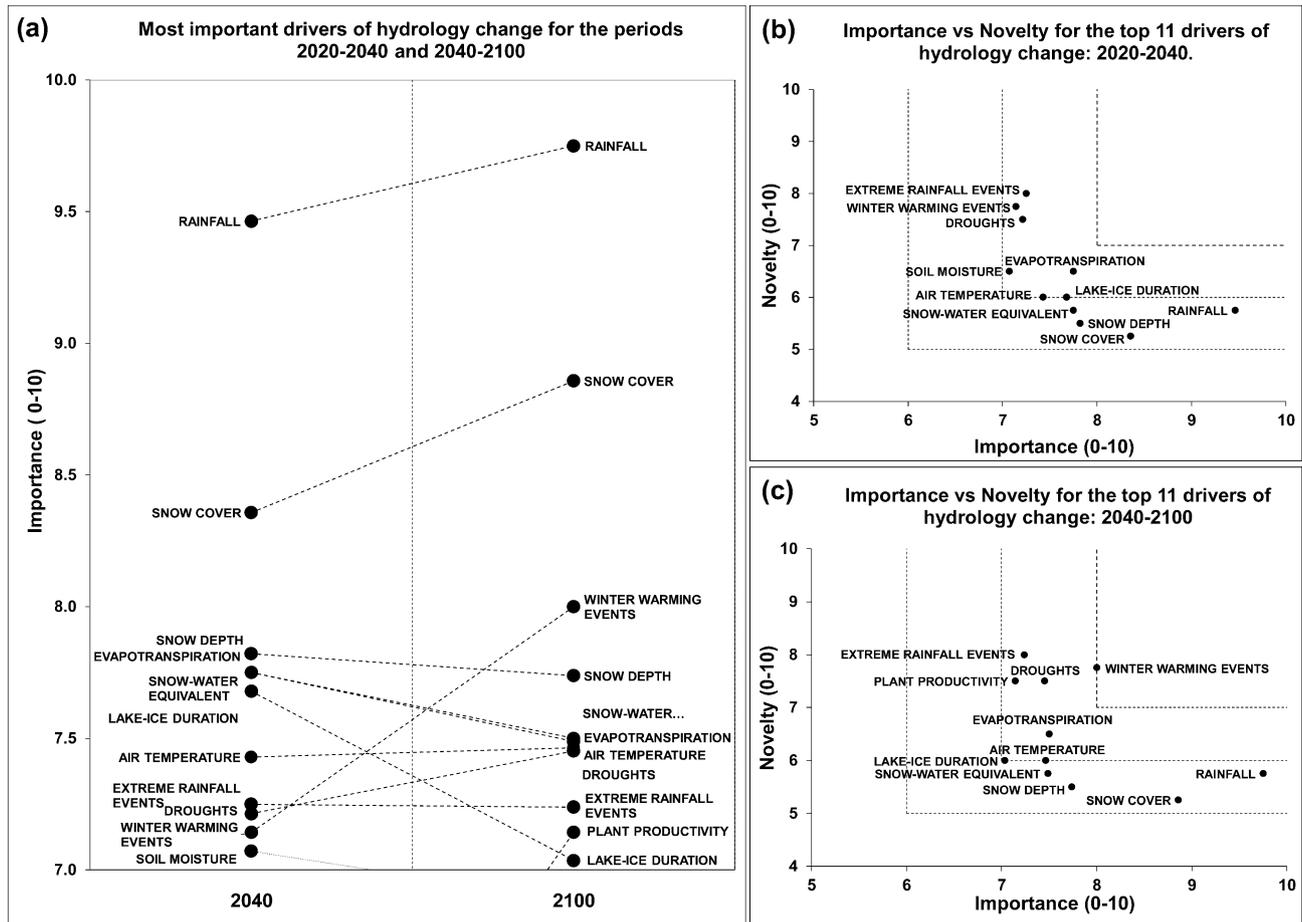


Fig. 4 **a** The eleven most important drivers of hydrology change for the periods 2020–2040 and 2040–2100. **b, c** Future research priorities identified through importance vs novelty for the most important drivers of hydrology change for the periods 2020–2040 and 2040–2100, respectively

Winter warming events

Direct and indirect effects of winter warming events on ecosystem change were identified as a research priority by all expert groups. In the study area, the frequency of winter warming events has been studied for the last century, showing a peak of events in the 1920s–30 s, and a stronger one during the last two decades (Vikhamar-Schuler et al. 2016). There are also a few studies on impacts of extreme winter warming events that sprung out of a collaboration with Indigenous Peoples, who had observed increasing ice layers in the snowpack after extreme winter warming events (Riseth et al. 2011). This studies show that winter warming events, mainly through altering the snow insulating effect and the plant available water in growing seasons, are a potential driver of the ‘browning’ of vegetation (declining biomass or productivity) recently observed in some parts of the Arctic (Phoenix and Bjerke, 2016). Bokhorst et al. (2009) observed a large decline (26%) in vegetation greenness (NDVI, normalized

difference vegetation index) after the severe winter warming event during December 2007, although this damage was followed by a quick (within 2 year) recovery (Bokhorst et al. 2012). The impacts on vegetation growth and other ecosystem processes by winter warming events are likely to intensify in the scenario of more frequent and intense events predicted for the coming decades (Vikhamar-Schuler et al. 2016).

Till now, there are only a few studies available in the Arctic area focusing on the direct and indirect impacts of extreme winter warming events on snow duration and properties, albedo, permafrost, microbial activity, vegetation dynamics, herbivore populations and biodiversity (e.g. Schimel et al. 2004; Callaghan et al. 2011; Sokolov et al. 2016; Barrere et al. 2018; Treharne et al. 2019). The impacts of these events still remain largely uncertain for most of the Arctic, including our study area. The most important research questions identified in this study (Supplementary material S4) cover most of the topics above, and include research questions such as “*What is the impact*

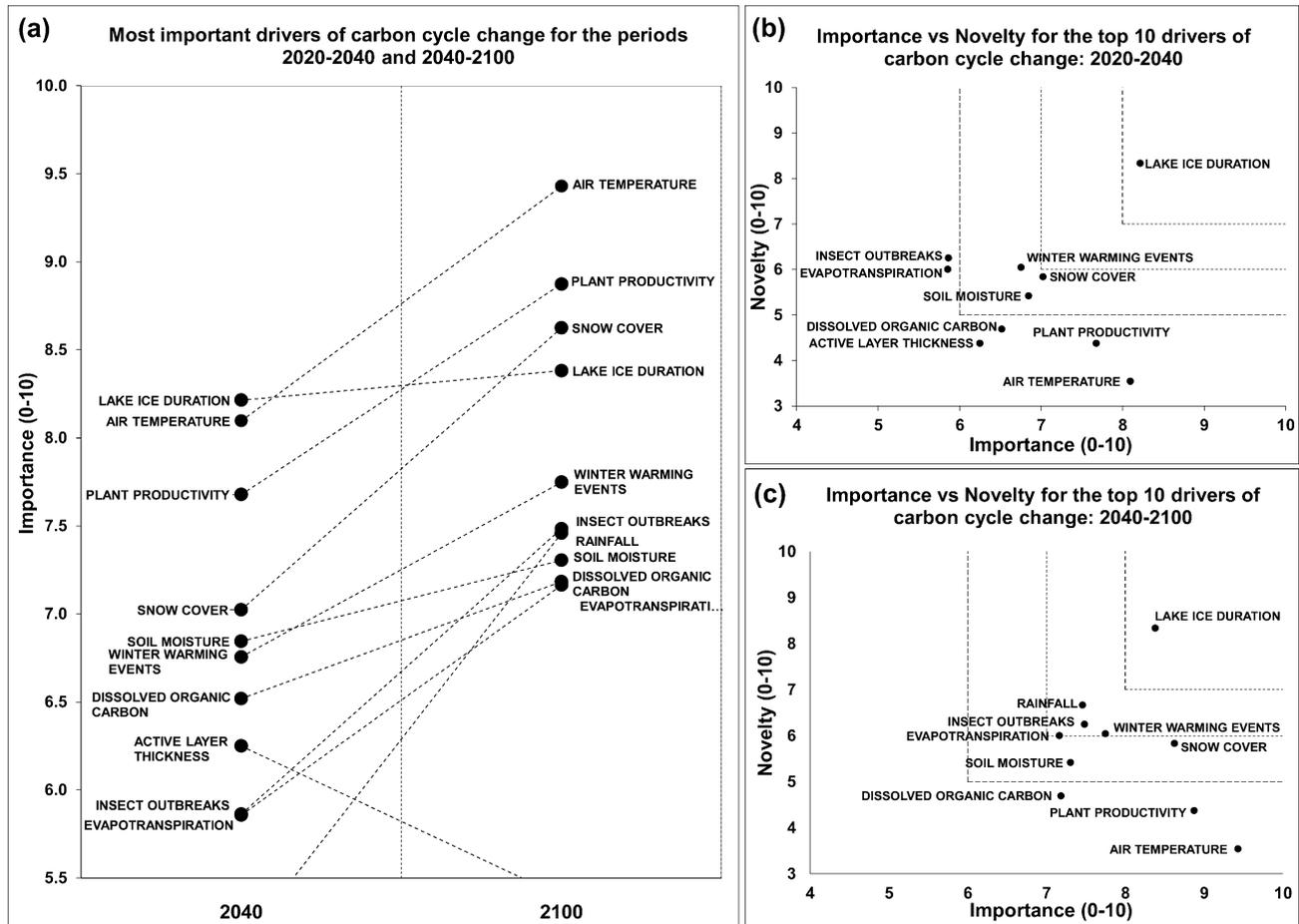


Fig. 6 a The ten most important drivers of carbon cycle change for the periods 2020–2040 and 2040–2100. b, c Importance vs novelty for the most important drivers of cycle change for the periods 2020–2040 and 2040–2100, respectively

the twenty-first century are largely expected in winter, when evapotranspiration rates are low (IPCC 2013), it is likely that, under a future warmer climate, soil moisture will decrease in summer. Nevertheless, these predictions (and hence the resulting consequences for ecosystems) are highly uncertain.

Studies on the direct and indirect impacts of evapotranspiration on local and regional air temperature (e.g. Ban-Weiss et al. 2011; Pearson et al. 2013) and on soil properties (soil moisture, thermal conductivity, and temperature) (e.g. Lawrence and Swensson 2011), exist from a few Arctic locations, but studies on the resulting impacts on plant productivity and microbial activity are lacking. All of these processes, in turn, require further attention in the study area. The most important research questions suggested by the experts (Supplementary material S4) cover most of these topics and include research questions such as “What is the potential for shifts in evapotranspiration to cause water deficits in contrasting landscape positions and on different timescales?”, and “What are the impacts of hydrological regime shifts on (i) vegetation dynamics, (ii)

ground temperatures, (iii) microbial activity and soil organic carbon decomposition, (iv) water flow, and the transport, delivery and fate of dissolved organics, and (v) the carbon balance?”.

A suggested way forward in the study area is to (1) implement continuous evapotranspiration monitoring, and expand and sustain the current precipitation monitoring network, to understand the changes in the water balance over the study region, (2) conduct manipulation studies to quantify ecosystem responses (e.g. plant-specific responses, soil temperature and moisture, soil microbial activity, and water flow and terrestrially derived compounds) to scenarios of increased evapotranspiration, and (3) improve the representation of the evapotranspiration-climate interactions in models.

Rainfall

Direct and indirect effects of rainfall on ecosystem change were identified as a research priority by four of the five expert groups: all but vegetation experts. In the study area,

an increase in rainfall has occurred especially since 1980 (Callaghan et al. 2010), with a dramatic increase in the magnitude of extreme rainfall events over the past century that have caused damage in infrastructures and destabilized mountain slopes (Jonasson et al. 2012). Impacts of increasing rainfall, such as the increased transport of dissolved organic matter (DOM) in water bodies, have been studied in the Torneträsk region (e.g. Kokfelt et al. 2009; Giesler et al. 2014). The increased DOM concentration in waterbodies may be enhanced in the long term due to permafrost thawing (e.g. Olefeldt and Roulet, 2012), and the larger amounts of plant biomass (e.g. Tang et al. 2018.). Karlsson et al. (2010) suggested that future increases in summer precipitation and loss of sporadic permafrost could lead to a net release of carbon to the atmosphere through respiration. The field manipulation studies that artificially increased summer precipitation do not show any significant impacts on the growth of vascular plants (e.g. Karlsson, 1985; Parsons et al. 1994; Keuper et al. 2012), but indicate that bryophytes may benefit from increased precipitation (Phoenix et al. 2001), which may increase ecosystem productivity given their substantial role in C cycling at high latitudes (Street et al. 2013).

Even if rainfall has been studied in the Torneträsk region for more than a century, different research gaps on the direct and indirect effects of rainfall on ecosystems needs to be addressed. As explained earlier, recent studies suggest that the future increase in summer rainfall is not likely to compensate the greater evapotranspiration water losses in the Torneträsk area (IPCC 2013). This imbalance can potentially result in reduced soil moisture, water flow, and organic matter transport, as well as altered vegetation and permafrost dynamics, which need further investigation in the area. Most of these topics were identified among the current research gaps suggested by the experts (Supplementary material S4), in addition to research questions such as “*What is the spatial and temporal effects of the rainfall-induced increases in evapotranspiration and vegetation productivity on the surface energy balance (latent heat and albedo effects)?*” and “*What will be the net effect of future changes in rainfall on the hydrologic system, and what impacts will it have on (i) the transport, delivery and fate of terrestrial carbon, (ii) plant productivity, (iii) permafrost dynamics, (iv) the carbon cycle?*”.

A suggested way forward in the study area is to (1) build a more robust and sustained precipitation and evapotranspiration monitoring network, to help reducing the uncertainties on the timing and magnitude of future changes in the water balance, (2) evaluate the impacts of increased rainfall on mountain permafrost, and (3) perform manipulation studies to assess the vegetation/permafrost/carbon cycle response to, in contrast to what has been assumed to date, a decrease in soil moisture.

Snow cover

Direct and indirect effects of snow cover on ecosystem change were identified as a research priority by three of the five expert groups: local climate, hydrology, and carbon cycle expert groups. In the Torneträsk area, mean snow depth has doubled over the 20th Century (Kohler et al. 2006), whilst snow cover duration has decreased significantly at both high and low elevations between 1978 and 2007 (0.1 and 0.12 week year⁻¹; Andrews et al. 2011). In addition, a long-term (49-year) record of snow profile stratigraphy showed increases in hard snow layers, and changes in snow hardness and dryness during early winter and spring (Johansson C. et al. 2011), mostly due to more intense and frequent abrupt winter temperature fluctuations recently occurring in the area (Vikhamar-Schuler et al. 2016). These changes in snow cover and properties have important consequences for arctic ecosystems and societies (Callaghan et al. 2011). The field snow addition by snowfence have resulted in substantial increases in ground temperature, active layer thickness, and growth and distribution of graminoids, in a peat plateau with permafrost in Torneträsk area (Johansson et al. 2013). Other studies have observed substantial vegetation frost-damage in response to warming-induced changes in snow properties (e.g. Bokhorst et al. 2009). Projections for the Torneträsk area indicate strong reductions in snow depth and cover over the twenty-first century (Brown et al. 2017), which may exacerbate the related impacts.

Even though a growing body of literature on the Arctic winter climatic change have shed light on the ecosystem responses to changes in snow properties (see Wipf and Rixen 2010; Cooper 2014; Bokhorst et al. 2016, and references therein), further advances in snow monitoring and modelling are required, and studies on the impacts of snow changes on ecosystem processes, such as the surface energy budget, seasonal biological and hydrological responses, and trophic-level interactions, deserve a greater attention in the study area. The most important research questions identified in this study (Supplementary material S4) cover most of those topics and include research questions such as “*What is the spatial distribution of snow depth and stratigraphy in the study area, and how does it affect soil moisture, soil temperatures, and soil microbial activity?*” and “*What is the balance between shorter snow-pack periods and anticipated greater snowfall, and how does it affect the timing of snowmelt and the related hydrological and stream ecological processes?*”.

A suggested way forward in the study area is to address major gaps that impede performing better projections of changes in snow properties: (1) monitoring gaps, by (i) extending the number of human-based and automatic measurements of snow properties, (ii) including other

sources of knowledge, such as traditional ecological knowledge (TEK) (Riseth et al. 2011), and (iii) developing and improving remote sensing techniques capable of retrieving accurate data on snow properties at relevant spatial and temporal scales; (2) experimental gaps, by performing studies of the impacts of a changing snow cover on (i) biological activities in autumn, (ii) trophic-level interactions, and (iii) microbial activity and the decomposition of organic matter in soils; (3) modelling gaps, by improving the representation of arctic snow cover, and the representation of snow-related processes (e.g. snowmelt, snow albedo, snow insulating capacity, and snow-wind and snow-freshwater ice interactions) in models.

Lake-ice duration

Direct and indirect effects of lake-ice duration on ecosystem change were identified as a research priority by three of the five expert groups: local climate, hydrology, and carbon cycle expert groups. Lake-ice duration has decreased substantially in the study area during the twentieth century, as observed in Lake Torneträsk (47 days decline during the twentieth century; Callaghan et al. 2010). Different studies have investigated the impacts of the declining lake-ice duration on ecosystems in the study area, including the effects on air temperature in the adjacent areas (Yang et al. 2011), lake primary productivity (Karlsson et al. 2009), and CO₂ (Denfeld et al. 2016) and CH₄ (Wik et al. 2014) emissions. These impacts are likely to intensify with the projected further shortening of lake-ice duration in the area (Prowse et al. 2012).

Studies on future lake-ice dynamics, and potential direct and indirect impacts on ecosystem processes such as aquatic primary productivity (e.g. Rühland et al. 2015), emissions of CO₂ and CH₄ (e.g. Wik et al. 2014; Denfeld et al. 2016), and the climate (e.g. Brown and Duguay 2010), exist from other locations across the Arctic. However, as identified in the expert elaborations (Supplementary material S4), there is a great need for accurate estimates of future lake-ice decline rates in the study area, and investigations on the resulting implications for the hydrologic system and the carbon cycle. In addition, the experts suggested other important research questions such as “*What are the future changes in lake-ice duration and its effects on the local climate of the Torneträsk area?*”, and “*What are the effects on stratification and water circulation patterns, and their implications for carbon cycling (that could be profound in a water body the size of Torneträsk)?*”.

A suggested way forward in the study area is to (1) perform modelling studies to obtain accurate estimates of

the future lake-ice decline rates, (2) integrate the future lake-ice dynamics and the resulting climate-hydrology-carbon cycle interactions into fine-scale models, in order to better assess the direct and indirect impacts of changing lake-ice conditions on (i) the climate, vegetation, ground temperatures, and the carbon cycle, on the adjacent ecosystems, and (ii) the water and sediment temperature, light penetration, water runoff, input of organic matter, primary productivity, and C fluxes, in water bodies.

Soil moisture

Direct and indirect effects of soil moisture on ecosystem change were identified as a research priority by three of the five expert groups: local climate, hydrology, and carbon cycle expert groups. As discussed earlier, projections indicate a substantial decrease in soil moisture through the twenty-first century, especially during summer (IPCC 2013). These projections, however, remain highly uncertain due to the unknown balance between increasing evapotranspiration and precipitation, and the changing vegetation cover (IPCC 2013). As explained for rainfall above, there are no studies that investigated plant responses to reduced soil moisture in the Torneträsk area. In addition, studies evaluating the effects of decreasing soil moisture on permafrost and the hydrologic system are, to our knowledge, lacking in the study area.

The key role of soil moisture in modulating relevant ecosystem processes and parameters, such as ground temperature, decomposition rates of organic matter, and the form and magnitude of soil carbon emissions, is well recognized in the literature (e.g. Lin 1980; Oertel et al. 2016). However, at a local scale, near-surface soil moisture depends on several processes (e.g. infiltration, drainage, and active layer thickening), weather conditions (e.g. wind speed and radiation), and geophysical properties (e.g. surface roughness, soil texture, and permeability), for which we lack understanding at relevant spatial and temporal scales. This makes changes in soil moisture heterogeneous and challenging to predict across the landscape. Recent efforts have focused on retrieving fine-resolution satellite soil moisture data from different Arctic locations, and its assimilation in models (e.g. Watts et al. 2014; Zwieback et al. 2019). Yet, these methodologies still have major limitations, such as spatial and temporal coverage, and their coarse resolution. The most important research questions identified in this study (Supplementary material S4) cover most of the above-mentioned topics, and include research questions such as “*What are the spatial and temporal patterns of soil moisture conditions in the Torneträsk area?*” and “*What are the impacts of changes in soil moisture for ground temperatures and primary productivity?*”.

A suggested way forward in the study area is to (1) improve the monitoring system, by (i) by developing an extensive and continuous soil moisture monitoring programme, with special focus on underrepresented areas, such as mountainous terrain, and (ii) developing and improving remote sensing techniques to acquire frequent and spatially extended high-resolution soil moisture data, supported by the higher number of in-situ measurements, (2) perform manipulation studies on vegetation, permafrost, and the carbon cycle, in contrasting landscape positions and locations, assuming a future decrease in soil moisture, and (3) reduce uncertainties in the predictions of future changes in temperature and precipitation to obtain more accurate predictions of the future water balance,

Droughts

Direct and indirect effects of droughts on ecosystem change were identified as a research priority by three of the five expert groups: local climate, permafrost and hydrology expert groups. Droughts are not causing major impacts on lowland ecosystems in the Torneträsk area at present (Bjerke et al. 2014), which has led to a scarce number of studies in the area. In contrast, numerous studies evaluating the effects of droughts on ecosystem processes such as plant productivity (e.g. Lotsch et al. 2005), soil moisture and ground water (e.g. Okkonen et al. 2010), the carbon cycling (e.g. Reichstein et al. 2013), fires (e.g. Kasischke and Turetsky 2006), soil respiration (e.g. Sowerby et al. 2008), and permafrost dynamics (e.g. Fisher et al. 2016), exist from several Arctic areas.

The current circumstances in the Torneträsk area may change in the future as droughts may become more frequent and intense in the Arctic (IPCC 2013). Some ongoing studies point towards this direction: the last major heat-wave in the Torneträsk area, in July 2018 (3rd warmest July since 1913, with mean daily air temperatures up to 23.3 °C) (ANS, 2020. Meteorological data from the Abisko Observatory, monthly mean 2000–01–01–2019–12–31), and the associated decrease in soil moisture, might have reduced maximum active layer thickness in areas of permafrost thawing relative to the previous year, which experienced a colder spring and summer (Johansson M. et al., in prep); warming is projected to replace birch forest areas by more fire-vulnerable pine species in some areas (Wolf et al. 2008). Hence, the impacts of droughts clearly deserve further research focus in the Torneträsk area. Most of the topics mentioned above have been identified in the experts' written elaborations (Supplementary material S4), in addition to research questions such as “*What is the relation between the Scandinavian (high-pressure) blocking of the jet stream, and the local meteorology in the study*

area, and how will its frequency change in the future?”, and “*What are the impacts of droughts on stream ecology and biogeochemistry?*”.

A suggested way forward in the study area is to (1) perform field manipulation studies to investigate (i) the plant-specific responses to more severe and frequent droughts, and (ii) the impacts of droughts on soil temperature and soil moisture in contrasting landscape positions and land cover types, and the resulting effect on soil respiration, (2) investigate, through monitoring and modelling, the impact of droughts (i) on lowland and mountain permafrost, and (ii) on streamflow and water chemistry, aquatic primary productivity, and C fluxes from water bodies, (3) conduct modelling studies to assess how long-term vegetation changes, together with the occurrence of severe droughts, may favour fire disturbances, and (4) integrate and upscale findings from points 1–3 in models, to obtain a comprehensive assessment of the overall impact of droughts on the carbon cycle at a landscape scale.

CONCLUSIONS

This expert evaluation of the importance and novelty of multiple ecosystem drivers in two future periods provides a comprehensive assessment of the current state of knowledge, and gives insights on research priorities surrounding ecosystem change in the Torneträsk area. The results further reveal the important knowledge gaps regarding the potential future impacts of different drivers. The most important research priorities identified include investigations of the current and potential effects on ecosystems brought on by altered frequency and intensity of winter warming events, evapotranspiration rates, rainfall, duration of snow cover and lake-ice, changed soil moisture, and droughts.

Because of the great complexity of arctic systems, a good understanding of the multiple causes of ecosystem change and the interactions between systems can often be best captured by focusing on a single location. The Torneträsk area, with its relatively small size, its great biological, meteorological and geomorphological diversity, and its unique datasets, is therefore suitable for such comprehensive analysis, and represents a microcosm of the Subarctic and the rapidly-transforming arctic ecosystems. The understanding obtained in this area can, despite the great diversity of arctic ecosystems, be applied in other arctic areas, and inform research efforts that, combined, can help improve future predictions. These predictions will provide local stakeholders with essential detailed information that will aid the development of mitigation plans and adaptation strategies.

Acknowledgements Open access funding provided by Lund University. We are grateful to the Department of Physical Geography and Ecosystem Science, Lund University for the grant received to promote research integration and advancement of early-career researchers at the department 2018. We are also grateful to Göran Gustafsson Stiftelse for contributing with funding, and to Thomas Holst and Lars Eklundh for constructive comments on the design of the study. This study has been made possible by data provided by the Abisko Scientific Research Station and the Swedish Infrastructure for Ecosystem Science (SITES). MJ and TVC are very grateful for support by INTERACT funded through the EU Horizon2020 programme (GA 871120).

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

REFERENCES

- Abisko Scientific Research Station (ANS) data. See <https://www.polar.se/abisko>
- ACIA. 2005. *Arctic climate impact assessment*. Cambridge, UK: Cambridge University Press.
- Allen, R.G., M. Smith, A. Perrier, and L.S. Pereira. 1994. An update for the definition of reference evapotranspiration. *ICID Bulletin* 43 : 1–34.
- Andersson, N.A., T.V. Callaghan, and P.S. Karlsson. 1996. The Abisko Scientific Research Station. *Ecological Bulletins* 45: 11–14.
- Andrews, C., J. Dick, C. Jonasson, and T.V. Callaghan. 2011. Assessment of biological and environmental phenology at a landscape level from 30 years of fixed date repeat photography in Northern Sweden. In *Multi-decadal changes in tundra environments and ecosystems: The international polar year back to the future project*, eds. Callaghan, T.V., and C.E. Tweedie. *Ambio* 40: 600–609.
- Ban-Weiss, G.A., G. Bala, L. Cao, J. Pongratz, and K. Caldeira. 2011. Climate forcing and response to idealized changes in surface latent and sensible heat. *Environmental Research Letters* 6: 034032.
- Barrere, M., F. Domine, M. Belke-Brea, and D. Sarrazin. 2018. Snowmelt events in autumn can reduce or cancel the soil warming effect of snow-vegetation interactions in the arctic. *American Meteorological Society* 31: 9507–9518.
- Bjerke, J.W., S.R. Karlsson, K.A. Høgda, E. Malnes, J.U. Jepsen, S. Lovibond, D. Vikhamar-Schuler, and H. Tommervik. 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.
- Björk, R.G., L. Klemmedtsson, U. Molau, J. Harndorf, A. Ödman, and R. Giesler. 2007. Linkages between N turnover and plant community structure in a tundra landscape. *Plant and Soil* 294: 247–261.
- Bokhorst, S., J.W. Bjerke, H. Tømmervik, T.V. Callaghan, and G.K. Phoenix. 2009. Winter warming events damage sub-Arctic vegetation: consistent evidence from an experimental manipulation and a natural event. *Journal of Ecology* 97: 1408–1415.
- Bokhorst, S., J.W. Bjerke, M.P. Davey, K. Taulavuori, E. Taulavuori, K. Laine, T.V. Callaghan, and J.K. Phoenix. 2010. Impacts of extreme winter warming events on plant physiology in a sub-Arctic heath community. *Physiologia Plantarum* 140: 128–140.
- Bokhorst, S., H. Tømmervik, T.V. Callaghan, G.K. Phoenix, and J.W. Bjerke. 2012. Vegetation recovery following extreme winter warming events in the sub-Arctic estimated using NDVI from remote sensing and handheld passive proximal sensors. *Environmental and Experimental Botany* 81: 18–25.
- Bokhorst, S., S.H. Pedersen, L. Brucker, O. Anisimov, J.W. Bjerke, R.D. Brown, D. Ehrlich, R.L.H. Essery, et al. 2016. Changing Arctic snow cover: A review of recent developments and assessment of future needs for observations, modelling, and impacts. *Ambio* 45: 516–537.
- Brown, L.C., and C. Duguay. 2010. The response and role of ice cover in lake-climate interactions. *Progress in Physical Geography* 34 : 671–704.
- Brown, J., O. J. Ferrians, J. A. Heginbottom, and E. S. Melnikov. 1998. Circum-arctic map of Permafrost and ground-ice conditions International Permafrost Association Standing Committee on Data Information and Communication (comp.). 2003. Circumpolar Active-Layer Permafrost System, Version 2.0 ed M Parsons and T Zhang (Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology) CD-ROM.
- Brown, R., D. VikhamarSchuler, O. Bulygina, K. Loujus, L. Mudryk, D. Yang. 2017. Arctic terrestrial snow cover. In: AMAP (Ed) Snow, Water, Ice and Permafrost in the Arctic (SWIPA) (pp. 25–64). Oslo: Arctic Monitoring and Assessment Programme (AMAP). ISBN 978-82-7971-101-8
- Callaghan, T.V., F. Bergholm, T.R. Christensen, C. Jonasson, U. Kokfelt, and M. Johansson. 2010. A new climate era in the sub-Arctic: Accelerating climate changes and multiple impacts. *Geophysical Research Letters* 37: L14705.
- Callaghan, T.V., M. Johansson, D. Ross, P.Y. Groisman, N. Labba, V. Radionov, R.S. Bradley, S. Blangy, et al. 2011. Multiple effects of changes in Arctic snow cover. *Ambio* 40: 32–45.
- Callaghan, T., C. Jonasson, T. Thierfelder, Z. Yang, H. Hedenås, M. Johansson, U. Molau, R. Van Bogaert, et al. 2013. Ecosystem change and stability over multiple decades in the Swedish Subarctic: complex processes and multiple drivers. *Philosophical Transactions of the Royal Society B* 368: e20120488.
- Christensen, T.R., T. Johansson, J. Åkerman, M. Mastepanov, N. Malmer, T. Friborg, P. Crill, and B.H. Svensson. 2004. Thawing subarctic permafrost: Effects on vegetation and methane emissions. *Geophysical Research Letters* 31: L04501. <https://doi.org/10.1029/2003GL018680>.
- Cohen, J., J.A. Screen, J.C. Furtado, M. Barlow, D. Whittleston, D. Coumou, J. Francis, K. Dethloff, et al. 2014. Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience* 7 : 627–637.
- Collins, M., R. Knutti, J. Arblaster, J. L. Dufresne, T. Fichet, P. Friedlingstein, X. Gao, W. J. Gutowski, et al. 2013. Long-term climate change: Projections, commitments and irreversibility. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker, T. Fichet, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Doschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge: Cambridge University Press, pp. 1029–1136, <https://doi.org/10.1017/CBO9781107415324.024>.
- Cooper, E.J. 2014. Warmer shorter winters disrupt Arctic terrestrial ecosystems. *Annual Review of Ecology Evolution and Systematics* 45: 271–295.

- Denfeld, B.A., P. Kortelainen, M. Rantakari, S. Sobek, and G.A. Weyhenmeyer. 2016. Regional variability and drivers of below ice CO₂ in boreal and subarctic lakes. *Ecosystems* 19: 461–476. <https://doi.org/10.1007/s10021-015-9944-z>.
- Giesler, R., S.W. Lyon, C.M. Mörth, J. Karlsson, E.M. Karlsson, E.J. Jantze, G. Destouni, and C. Humborg. 2014. Catchment-scale dissolved carbon concentrations and export estimates across six subarctic streams in northern Sweden. *Biogeosciences* 11: 525–537. <https://doi.org/10.5194/bg-11-525-2014>.
- Hedenäs, H., B.Å. Carlsson, U. Emanuelsson, A. Headley, C. Jonasson, B.M. Svensson, and T.V. Callaghan. 2012. Changes versus homeostasis in alpine and subalpine vegetation over three decades in the sub-Arctic. *Ambio* 41: 187–196. <https://doi.org/10.1007/s13280-012-0312-3>.
- IPCC. 2013. Climate Change 2013: The Physical Science Basis, in Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker, T.F., D. in, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.). Cambridge, New York: Cambridge University Press.
- Johansson, M., T.R. Christensen, J. Åkerman, and T.V. Callaghan. 2006. What determines the current presence or absence of permafrost in the Torneträsk region, a subarctic landscape in northern Sweden? *Ambio* 35: 190–197.
- Johansson, C., V.A. Pohjola, C. Jonasson, and T.V. Callaghan. 2011a. Multi-decadal changes in snow characteristics in sub-arctic Sweden. *Ambio* 40: 566–574.
- Johansson, M., J. Åkerman, F. Keuper, T.R. Christensen, H. Lantuit, and T.V. Callaghan. 2011b. Past and present permafrost temperatures in the Abisko area: Redrilling of boreholes. *Ambio* 40: 558–565. <https://doi.org/10.1007/s13280-011-0163-3>.
- Johansson, M., C. Jonasson, M. Sonesson, and T.R. Christensen. 2012. The man, the myth, the legend: Professor Terry V. Callaghan and his 3M concept. *Ambio* 41: 175–177.
- Johansson, M., T.V. Callaghan, J. Bosiö, J. Åkerman, M. Jackowicz-Korcynski, and T.R. Christensen. 2013. Rapid responses of permafrost and vegetation to experimentally increased snow cover in sub-arctic Sweden. *Environmental Research Letters*. 8: 035025.
- Jonasson, C., M. Sonesson, T. Christensen, and T.V. Callaghan. 2012. Environmental monitoring and research in the Abisko Area—an overview. *Ambio* 41: 178–186.
- Karlsson, P.S. 1985. Effects of water and mineral nutrient supply on *adeciduous* and an evergreen dwarf shrub-*Vaccinium uliginosum* L. and *V. visticidaea* L. *Holarctic Ecology* 8: 1–8.
- Karlsson, J., P. Byström, J. Ask, P. Ask, L. Persson, and M. Jansson. 2009. Light limitation of nutrient-poor lake ecosystems. *Nature* 460: 506–509.
- Karlsson, J., T.R. Christensen, P. Crill, J. Förster, D. Hammarlund, M. Jackowicz-Korcynski, U. Kokfelt, C. Roehm, et al. 2010. Quantifying the relative importance of lake emissions in the carbon budget of a subarctic catchment. *Journal of Geophysical Research* 115: G03006. <https://doi.org/10.1029/2010JG001305>.
- Kasischke, E.S., and M.R. Turetsky. 2006. Recent changes in the fire regime across the North American boreal region spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters* 33: L09703.
- Keuper, F., W. Parmentier, D. Blok, P.M. van Bodegom, E. Dorrepaal, J.R. van Hal, R.S.P. van Logtestijn, and R. Aerts. 2012. Tundra in the rain: Differential vegetation responses to three years of experimentally doubled summer precipitation in Siberian Shrub and Swedish Bog Tundra. *Ambio* 41: 269–280. <https://doi.org/10.1007/s13280-012-0305-2>.
- Kivinen, S., S. Rasmus, K. Jylhä, and M. Laapas. 2017. Long-term climate trends and extreme events in Northern Fennoscandia (1914–2013). *Climate* 5: 16. <https://doi.org/10.3390/cli5010016>.
- Kohler, J., O. Brandt, M. Johansson, and T.V. Callaghan. 2006. A long record of Arctic snow-depth measurements from Abisko, northern Sweden, 1913–2002. *Polar Research*. 25: 91–113. <https://doi.org/10.1111/j.1751-8369.2006.tb00026.x>.
- Kokfelt, U., U. Rosén, K. Schoning, T.R. Christensen, J. Förster, J. Karlsson, N. Reuss, M. Rundgren, et al. 2009. Ecosystem responses to increased precipitation and permafrost decay in subarctic Sweden inferred from peat and lake sediments. *Global Change Biology* 15: 1652–1663. <https://doi.org/10.1111/j.1365-2486.2009.01880.x>.
- Lantmäteriet, G.S.D. 2006. Vegetation map of Abisko 30I and Rensjön 30J. Produced and digitized by Lantmäteriet GSD. Scale 1: 100000.
- Lawrence, D.M., and S.C. Swenson. 2011. Permafrost response to increasing Arctic shrub abundance depends on the relative influence of shrubs on local soil cooling versus large-scale climate warming. *Environmental Research Letters* 6: 045504.
- Lin, J.D. 1980. On the force-restore method for prediction of ground surface temperature. *Journal of Geophysical Research: Oceans* 85: 3251–3254.
- Lotsch, A., M.A. Friedl, B.T. Anderson, and C.J. Tucker. 2005. Response of terrestrial ecosystems to recent northern hemispheric drought. *Geophysical Research Letters* 32: L06705.
- Metcalfe, D.B., T.D.G. Hermans, J. Ahlstrand, M. Becker, M. Berggren, R.G. Björk, M.P. Björkman, and D. Blok. 2018. Patchy field sampling biases understanding of climate change impacts across the Arctic. *Nature Ecology and Evolution* 2: 1443–1448.
- Oertel, C., J. Matschullat, K. Zurba, F. Zimmermann, and S. Erasmii. 2016. Greenhouse gas emissions from soils—a review. *Chemie der Erde* 76: 327–352.
- Okkonen, J., M. Jyrkama, and B. Klove. 2010. A conceptual approach for assessing the impact of climate change on groundwater and related surface waters in cold regions (Finland). *Hydrogeology Journal* 18: 429–439.
- Olefeldt, D., and N.T. Roulet. 2012. Effects of permafrost and hydrology on the composition and transport of dissolved organic carbon (DOC) in a subarctic peatland complex. *Journal of Geophysical Research Atmospheres* 117: 1005.
- Park, H., H. Yabuki, and T. Ohata. 2012. Analysis of satellite and model datasets for variability and trends in Arctic snow extent and depth, 1948–2006. *Polar Science* 6: 23–37.
- Parsons, A.N., J.M. Welker, P.A. Wookey, M.C. Press, T.V. Callaghan, and J.A. Lee. 1994. Growth responses of four subarctic dwarf shrubs to simulated environmental-change. *Journal of Ecology* 82: 307–318.
- Pearson, R.G., S.J. Phillips, M.M. Loranty, P.S.A. Beck, T. Damoulas, S.J. Knight, and S.J. Goetz. 2013. Shifts in Arctic vegetation and associated feedbacks under climate change. *Nature Climate Change* 3: 673–677.
- Phoenix, G.K., and J.W. Bjerke. 2016. Arctic browning: extreme events and trends reversing arctic greening. *Global Change Biology* 22: 2960–2962. <https://doi.org/10.1111/gcb.13261>.
- Phoenix, G.K., D. Gwynn-Jones, T.V. Callaghan, D. Sleep, and J.A. Lee. 2001. Effects of global change on a sub-Arctic heath: Effects of enhanced UV-B radiation and increased summer precipitation. *Journal of Ecology* 89: 256–267. <https://doi.org/10.1046/j.1365-2745.2001.00531.x>.
- Prowse, T., K. Alfredsen, S. Beltaos, B. Bonsal, C. Duguay, A. Korhola, J. McNamara, W.F. Vincent, et al. 2012. Arctic freshwater ice and its climatic role. *Ambio* 40: 46–52.
- Reichstein, M., M. Bahn, P. Ciais, D. Frank, M.D. Mahecha, S.I. Seneyratne, J. Zscheischler, C. Beer, et al. 2013. Climate extremes and the carbon cycle. *Nature* 500: 287–295.
- Ridefelt, H., B. Eitzelmüller, J. Boelhouwers, and C. Jonasson. 2008. Statistic-empirical modelling of mountain permafrost

- distribution in the Abisko region, sub-arctic northern Sweden. *Norsk Geografisk Tidsskrift—Norwegian Journal of Geography* 62: 278–289.
- Riseth, J.A., H. Tømmervik, E. Helander-Renvall, N. Labba, C. Johansson, E. Malnes, J.W. Bjerke, C. Jonsson, et al. 2011. Sámi traditional ecological knowledge as a guide to science: Snow, ice and reindeer pasture facing climate change. *Polar Record* 47: 202–217.
- Rühland, K., A.M. Paterson, and J.P. Smol. 2015. Lake diatom response to warming: Reviewing the evidence. *Journal of Paleolimnology* 54: 1–35.
- Schimel, J.P., C. Bilbrough, and J.M. Welker. 2004. Increased snow depth affects microbial activity and nitrogen mineralization in two Arctic tundra communities. *Soil Biology and Biochemistry* 36: 217–227.
- Smith, B., D. Wårlind, A. Arneeth, T. Hickler, P. Leadley, J. Siltberg, and S. Zaehle. 2014. Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model. *Biogeosciences* 11: 2027–2054.
- Soja, A.J., N.M. Tchepakova, N.H.F. French, M.D. Flannigan, H.H. Shugart, B.J. Stocks, A.I. Sukhinin, E.I. Parfenova, et al. 2007. Climate-induced boreal forest change: Predictions versus current observations. *Global and Planetary Change* 56: 274–296.
- Sokolov, A.A., N.A. Sokolova, R.A. Ims, L. Brucker, and D. Ehrlich. 2016. Emergent rainy winter warm spells may promote boreal predator expansion into the Arctic. *Arctic* 69: 121–129. <https://doi.org/10.14430/arctic4559>.
- Sowerby, A., B.A. Emmett, A. Tietema, and B. Claus. 2008. Contrasting effects of repeated summer drought on soil carbon efflux in hydric and mesic heathland soils. *Global Change Biology* 14: 2388–2404.
- Street, L.E., J.-A. Subke, M. Sommerkorn, V. Sloan, H. Ducrottoy, G.K. Phoenix, and M. Williams. 2013. The role of mosses in carbon uptake and partitioning in arctic vegetation. *New Phytologist* 199: 163–175. <https://doi.org/10.1111/nph.12285>.
- Sundqvist, M.K., N.J. Sanders, and D. Wardle. 2013. Community and ecosystem responses to elevational gradients: Processes, mechanisms, and insights for global change. *Annual Review of Ecology Evolution and Systematics* 44: 261–280.
- Sutherland, W., E. Fleishman, M. Mascia, J. Pretty, and M. Rudd. 2011. Methods for collaboratively identifying research priorities and stemming issues in science and policy. *Methods in Ecology and Evolution* 2: 238–247.
- Tang, J., P.A. Miller, A. Persson, D. Olefeldt, P. Pilesjö, M. Heliasz, M. Jackowicz-Korczynski, Z. Yang, B. Smith, T.V. Callaghan, and T.R. Christensen. 2015. Carbon budget estimation of a subarctic catchment using a dynamic ecosystem model at high spatial resolution. *Biogeosciences* 12: 2791–2808.
- Tang, J., A. Yurova, G. Schurgers, P. Miller, S. Olin, B. Smith, M. Siewert, D. Olefeldt, et al. 2018. Drivers of dissolved organic carbon export in a subarctic catchment: Importance of microbial decomposition, sorption-desorption, peatland and lateral flow. *Science of the Total Environment* 622–623: 260–274.
- Treharne, R., J.W. Bjerke, H. Tømmervik, L. Stendardi, and G.K. Phoenix. 2019. Arctic browning: Impacts of extreme climatic events on heathland ecosystem CO₂ fluxes. *Global Change Biology* 25: 489–503.
- Van Bogaert, R., K. Haneca, J. Hoogesteger, C. Jonasson, M. De Dapper, and T.V. Callaghan. 2011. A century of tree line changes in sub-Arctic Sweden shows local and regional variability and only a minor influence of 20th century climate warming. *Journal of Biogeography* 38: 907–921.
- Vikhamar-Schuler, D., K. Isaksen, and J.E. Haugen. 2016. Changes in winter warming events in the Nordic Arctic Region. *Journal of climate* 29 : 6223–6244.
- Walsh, J.E. 2014. Intensified warming of the Arctic: Causes and impacts on middle latitudes. *Global and Planetary Change* 117: 52–63. <https://doi.org/10.1016/j.gloplacha.2014.03.003>.
- Watts, J.D., J.S. Kimball, F.J.W. Parmentier, T. Sachs, J. Rinne, D. Zona, W. Oechel, T. Tagesson, et al. 2014. A satellite data driven biophysical modeling approach for estimating northern peatland and tundra CO₂ and CH₄ fluxes. *Biogeosciences* 11 : 1961–1980. <https://doi.org/10.5194/bg-11-1961-2014>.
- Wielgolaski, F.E. 2005. History and environment of the Nordic mountain birch. In *Plant ecology, herbivory, and human impact in nordic mountain birch forests*, vol. 180, ed. F.E. Wielgolaski, 3–18. New York: Springer.
- Wik, M., B.F. Thornton, D. Bastviken, S. MacIntyre, R.K. Varner, and P.M. Crill. 2014. Energy input is primary controller of methane bubbling in subarctic lakes. *Geophysical Research Letters* 41: 555–560. <https://doi.org/10.1002/2013GL058510>.
- Wipf, S., and C. Rixen. 2010. A review of snow manipulation experiments in Arctic and alpine tundra ecosystems. *Polar Research* 29: 95–109.
- Wolf, A., T.V. Callaghan, and K. Larson. 2008. Future changes in vegetation and ecosystem function of the Barents region. *Climatic Change* 87: 51–73.
- Yang, Z., E. Hanna, and T.V. Callaghan. 2011. Modelling surface-air-temperature variation over complex terrain around Abisko, Swedish Lapland: uncertainties of measurements and models at different scales. *Geografiska Annaler Series A Physical Geography* 93: 89–112. <https://doi.org/10.1111/j.1468-0459.2011.00005.x>.
- Young, M.C., F.W. Zwiers, N.P. Gillett, and A.J. Cannon. 2017. Attributing extreme fire risk in Western Canada to human emissions. *Climatic Change* 144: 365–379.
- Zwieback, S., S. Westermann, M. Langer, J. Boike, P. Marsh, and A. Berg. 2019. Improving permafrost modeling by assimilating remotely sensed soil moisture. *Water Resources Research* 55: 1814–1832.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

AUTHOR BIOGRAPHIES

Didac Pascual (✉) is a PhD candidate in Physical Geography and Ecosystem Science at Lund University in Sweden. His work aims to improve the understanding and future predictions of ecosystem change in subarctic regions.
Address: Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden.
e-mail: didac.pascual@nateko.lu.se

Jonas Åkerman is an Associate Professor (emeritus) in Physical Geography and Ecosystem Science at Lund University in Sweden. His work covers long time monitoring (1972-ongoing) of geocryological, ecological processes and climate change in Arctic (Svalbard) and subarctic (North Sweden) regions.
Address: Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden.
e-mail: jonas.akerman@nateko.lu.se

Marina Becher is a State geologist at Geological Survey of Sweden. Her research interest includes periglacial processes, acid sulphate soils and digital mapping.
Address: Geological Survey of Sweden, Box 670, 751 28 Uppsala, Sweden.
e-mail: marina.becher@sgu.se

Terry V. Callaghan is a Professor of Arctic Biology at the University of Sheffield, UK, Professor of Botany at the Tomsk State University, Russia, and Member of the Royal Swedish Academy of Sciences, Sweden. His research interests include Arctic Ecology, climate change, traditional knowledge and science diplomacy.

Address: Alfred Denny Building, University of Sheffield, Western Bank, Sheffield S10 2TN, UK.

Address: Department of Botany, National Research Tomsk State University, 36 Lenin Ave., Tomsk, Russia 634050.

e-mail: terry_callaghan@btinternet.com

Torben R. Christensen is Professor of Arctic Biogeochemistry at the Arctic Research Centre, Aarhus University, Denmark. His research is on ecosystem-atmosphere interactions with particular attention to ecosystems responses to climate variability and change in Arctic environments. Special focus is on processes relating to carbon cycling and greenhouse gas exchanges. He is currently the Scientific Leader of the Greenland Ecosystem Monitoring Program and also Director of the Zackenberg Research Station in NE Greenland.

Address: Department of Bioscience, Faculty of Technical Sciences, Aarhus University, Frederiksborgvej 399, 4000 Roskilde, Denmark.
e-mail: torben.christensen@bios.au.dk

Ellen Dorrepaal is an Associate Professor at the Climate Impact Research Centre, Umeå University in Sweden. Her research focuses on ecosystems in cold areas and include questions such as how do plants and their interactions control ecological processes, how do different plant species or groups of plants vary in their responses to climate change or their effects on ecosystem functioning, and what does this mean for the feedbacks of northern ecosystems to climate change.

Address: Climate Impacts Research Centre, Department of Ecology and Environmental Science, Umeå University, 90187 Umeå, Sweden.
e-mail: ellen.dorrepaal@umu.se

Urban Emanuelsson is Professor at the Swedish Biodiversity Centre situated at the Swedish University of Agricultural Sciences. Her research interests include climate change, cultural landscape development and sustainable management of biodiversity.

Address: Swedish Biodiversity Centre, Swedish University of Agricultural Sciences, Mobergavägen 19, 373 54 Senoren, Sweden.

e-mail: urban.emanuelsson@slu.se

Reiner Giesler is a professor in terrestrial ecology at Umeå University, Sweden. His research interests include biogeochemical processes in terrestrial and aquatic environments with focus on climate change effects in high-latitude ecosystems.

Address: Climate Impacts Research Centre, Department of Ecology and Environmental Science, Umeå University, 90187 Umeå, Sweden.

e-mail: reiner.giesler@umu.se

Dan Hammarlund is a Professor of Quaternary Geology at Lund University. His research focusses on ecosystem responses to climate change on decadal to millennial time scales based on lake sediments and peat deposits. He has studied Holocene tree-line migration and permafrost dynamics in the Torneträsk area and other parts of the Scandes Mountains.

Address: Department of Geology, Lund University, Sölvegatan 12, 223 62 Lund, Sweden.

e-mail: dan.hammarlund@geol.lu.se

Edward Hanna is Professor of Climate Science and Meteorology at the University of Lincoln, UK, and the World Climate Research Programme Climate & Cryosphere representative on the Ice Sheet Mass Balance and Sea Level (ISMAL) Expert Group. Research areas include ice sheets and high-latitude climate change. International

Journal of Climatology, Royal Meteorological Society, Editor's Award 2017.

Address: School of Geography, Think Tank, Roston Way, Lincoln LN6 7FL, UK.

e-mail: ehanna@lincoln.ac.uk

Annika Hofgaard is a Senior Scientist (Professor level) at the Norwegian Institute for Nature Research, Norway. Her research interests include vegetation-climate interactions with main focus on subarctic and subalpine woody vegetation.

Address: Norwegian Institute for Nature Research, Torgarden, P.O. Box 5685, 7485 Trondheim, Norway.

e-mail: annika.hofgaard@nina.no

Hongxiao Jin is currently a postdoc in the Department of Environmental Engineering at the Technical University of Denmark, working on soil moisture and evapotranspiration using satellite, UAV, and SVAT models. He did his Ph.D. and postdoc researches in Physical Geography and Ecosystem Science at Lund University, working on remote sensing of Northern Europe vegetation phenology.

Address: Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden.

Address: Department of Environmental Engineering, Technical University of Denmark, 2800 Kgs., Lyngby, Denmark.

e-mail: honji@env.dtu.dk

Cecilia Johansson is an Associate Professor in meteorology at Uppsala University in Sweden. Her research interests include climate change in the Arctic and specifically changes in the snowpack.

Address: Department of Earth Sciences, Uppsala University, Villavägen 16, 752 36 Uppsala, Sweden.

e-mail: Cecilia.johansson@met.uu.se

Christer Jonasson is an Associate Professor in Physical Geography, Uppsala University in Sweden. His work covers process geomorphology, ecological processes, extreme meteorological events and climate change in subarctic regions.

Address: Department of Social and Economic Geography, Uppsala University, Box 513, 751 20 Uppsala, Sweden.

e-mail: christer.jonasson@kultgeog.uu.se

Jonatan Klaminder is an associate professor in Environmental Science at Umeå University. His field of research includes biogeochemistry of arctic soils and their functioning under natural and anthropogenic stressors.

Address: Climate Impacts Research Centre, Department of Ecology and Environmental Science, Umeå University, 90187 Umeå, Sweden.

e-mail: Jonatan.klaminder@umu.se

Jan Karlsson is a Professor of Aquatic Biogeochemistry at Umeå University, Sweden, and the director of the Climate Impacts Research Centre (CIRC). His research interests include climate impacts on aquatic biogeochemistry.

Address: Climate Impacts Research Centre, Department of Ecology and Environmental Science, Umeå University, 90187 Umeå, Sweden.

e-mail: jan.p.karlsson@umu.se

Erik Lundin is a research engineer at the Swedish Polar Research Secretariat. His work aims at improving the environmental monitoring programme and data accessibility at the Abisko Scientific Station.

Address: Swedish Polar Research Secretariat, Luleå tekniska universitet, 971 87 Luleå, Sweden.

e-mail: erik.lundin@polar.se

Anders Michelsen is professor in physiological ecology at University of Copenhagen, Denmark. His field of research is biogeochemistry and plant ecology, with particular focus on high-latitude ecosystems and impacts of climate change.

Address: Department of Biology, University of Copenhagen, Universitetsparken 15, 2100 Copenhagen Ø, Denmark.
e-mail: andersm@bio.ku.dk

David Olefeldt is an Assistant Professor and Campus Alberta Innovates Program Research Chair in Wetland and Catchment Science at the University of Alberta, Canada. His research focuses on the impacts of disturbances on ecosystem carbon cycling and water resources, particularly in northern regions.

Address: Department of Renewable Resources, University of Alberta, 751 General Services Building, Edmonton T6G 2H1, Canada.
e-mail: olefeldt@ualberta.ca

Andreas Persson is Associate Professor at Lund University, Sweden. His research interests include hydrological and landscape changes in relation to climate change. A certain focus for more than a decade has been in permafrost hydrology and its connection to the carbon balance, both from a field measurement and a modelling perspective.

Address: Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden.
e-mail: andreas.persson@nateko.lu.se

Gareth K. Phoenix is a Professor of Plant and Global Change Ecology at the University of Sheffield. His research interests include the impacts of climate change on arctic and upland ecosystems, including plant and soil responses and consequences for biogeochemical cycling.

Address: Department of Animal and Plant Sciences, University of Sheffield, Western Bank, Sheffield S10 2TN, UK.
e-mail: g.phoenix@sheffield.ac.uk

Zofia Rączkowska is a Professor at Institute of Geography and Spatial Organisation Polish Academy of Sciences. Her research interests include subarctic geomorphology, geocology and climate change.

Address: Department of Geoenvironmental Research, Institute of Geography and Spatial Organisation PAS, Św. Jana 22, 31-018 Kraków, Poland.
e-mail: raczk@zg.pan.krakow.pl

Riikka Rinnan is a Professor in Ecosystem-Atmosphere Interactions at University of Copenhagen, Denmark. Her research interests include climate change impacts on terrestrial ecosystems in the Arctic, with focus on exchange of volatile organic compounds.

Address: Department of Biology, University of Copenhagen, Universitetsparken 15, 2100 Copenhagen Ø, Denmark.
Address: Center for Permafrost (CENPERM), University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K, Denmark.
e-mail: riikka@bio.ku.dk

Lena Ström is a Professor of Biogeochemical Processes at Lund University in Sweden. Her research interests include wetland biogeochemistry with focus on how functional diversity of plants and microorganisms effect the carbon cycle and greenhouse gas balance of temperate to arctic wetland ecosystems.

Address: Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden.
e-mail: lena.strom@nateko.lu.se

Jing Tang is a researcher at both Lund University and University of Copenhagen. She is an ecosystem modeller with main focus on arctic vegetation dynamics, BVOC emissions and water and ecosystem interactions in high latitudes.

Address: Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden.

Address: Department of Biology, University of Copenhagen, Universitetsparken 15, 2100 Copenhagen Ø, Denmark.

Address: Center for Permafrost (CENPERM), University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K, Denmark.
e-mail: jing.tang@bio.ku.dk

Ruth K. Varner is a Professor of Biogeochemistry in the Department of Earth Sciences and Institute for the Study of Earth, Oceans and Space at the University of New Hampshire. Her research focuses on exchange of radiatively important trace gasses from Arctic, temperate and tropical ecosystems. Her recent research combines measurements, modelling and remote sensing to scale emissions of methane and its isotopologues from the pan-Arctic region.

Address: Department of Earth Sciences, University of New Hampshire, Morse Hall Rm 455, 8 College Rd., Durham, NH 03824, USA.
e-mail: ruth.varner@unh.edu

Philip Wookey is Professor of Ecosystem Science at the University of Stirling, Scotland, UK. His research focuses on the potential effects of environmental change on the structure and function (specifically nutrient cycling, soil organic matter dynamics and trace gas exchanges) of Arctic and boreal terrestrial ecosystems. He has worked in the Fennoscandian mountains, on Svalbard, in Canada, northern Iceland and the North Slope of Alaska. Philip is former Chair of the International Tundra Experiment (ITEX) and the Terrestrial Working Group of the International Arctic Science Committee (IASC).

Address: Biology and Environmental Sciences, School of Natural Sciences, University of Stirling, Stirling FK9 4LA, Scotland, UK.
e-mail: philip.wookey1@stir.ac.uk

Margareta Johansson is an Associate Professor at Lund University in Sweden. Her research interests include climate change in the Arctic and its impacts focusing on permafrost.

Address: Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden.
e-mail: margareta.johansson@nateko.lu.se