

Climate-Ecological Observatory for Arctic Tundra (COAT)

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Keywords: Adaptive monitoring, climate change, ecological monitoring, ecosystem based monitoring, food-web, long-term, management, terrestrial

1. Introduction

1.1 Background

Arctic tundra is one of the Earth's largest terrestrial biomes comprising the terrestrial ecosystems north of the continuous boreal forest. A predicted average temperature increase, of up to 10 °C by the turn of the century (Hansen et al. 2014; Hanssen-Bauer et al. 2019) will result in large and unforeseeable impacts on these ecosystems that will have pervasive implications locally and globally (CAFF 2013; Ims and Ehrich 2013; Meltotte et al. 2013). The Climate Ecological Observatory for Arctic Tundra (COAT) is a response to the urgent international calls for establishment of scientifically robust observation systems that will enable long-term, real-time detection, documentation, understanding and predictions of climate impacts on Arctic tundra ecosystems. COAT aims to be a fully ecosystem-based, long-term, adaptive monitoring programme, based on a food-web approach (Ims et al. 2013; www.coat.no). It is implemented from a peer reviewed Science Plan (Ims et al. 2013) based on a comprehensive review of the scientific literature on the functioning, structure and known drivers of terrestrial Arctic ecosystems. COAT focuses on two Norwegian Arctic regions, the Low Arctic Varanger peninsula and high Arctic Svalbard (Figure 1) that provide pertinent contrasts in Arctic tundra system complexity and climate and management regimes. COAT Svalbard is an essential component of the Svalbard Integrated Arctic Earth Observing System (SIOS) and serves to optimize and integrate the ecosystem-based terrestrial monitoring. This chapter will summarize the COAT Svalbard programme, with the goal of opening an avenue to increased integration of data within the SIOS community.

1.2 Climate impact path models

Understanding the functioning and structure of food webs is a key for predicting the response of tundra ecosystems to drivers of change (Post et al. 2009). The Svalbard tundra food web is relatively simple (Box 1), although the interactions between trophic levels can result in complex dynamics (Ims et al. 2013). COAT Svalbard contains six monitoring modules (five food web modules and a crosscutting climate module) (Figure 2). Each of the five food web modules (Box 2) is based on a *conceptual model* that outlines a set of *monitoring targets* in terms of climate sensitive key species or functional species groups in the tundra food web and *a priori* hypotheses for their key process relations. Climate and environmental management interventions are included as the main drivers of these relations. The purpose of the conceptual food web is to form a basic framework for data-driven causal analyses and predictions of climatic effects on the monitoring targets, quantify relationships between the monitoring targets and infer how management could be effective in mitigating predicted unwanted effects. Indeed, as COAT aims to be management relevant,

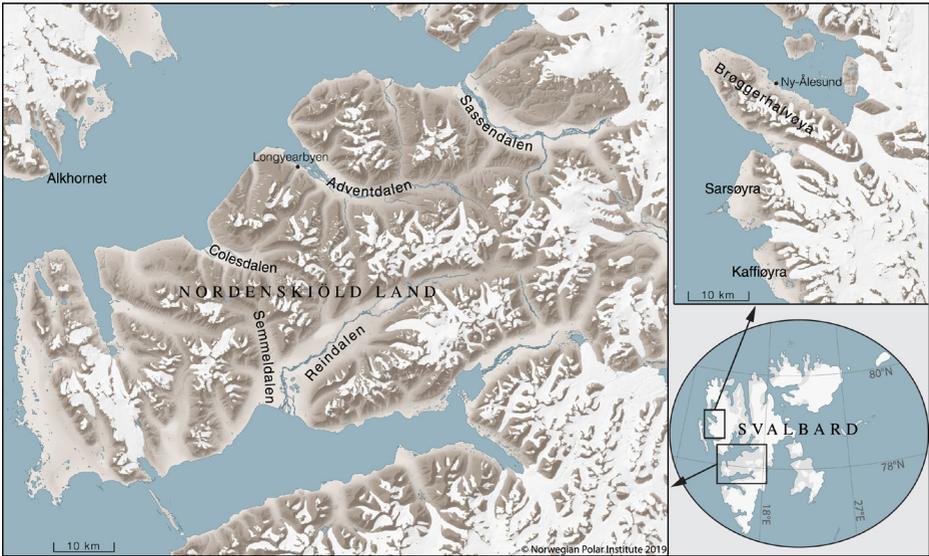


Figure 1: Map of the COAT Svalbard study regions (lower right) in Nordenskiöld Land (left) and Forlandssundet (Brøggerhalvøya, Sarsøya and Kaffløyra) (upper right). Figure: Bernt Bye/NPI.

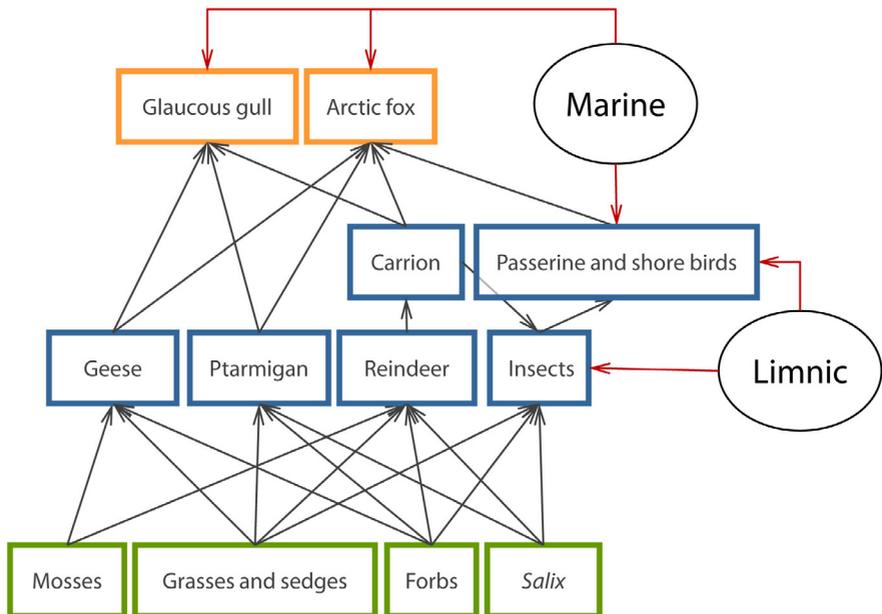
the conceptual models particularly highlight monitoring targets and process relations that may be subjected to local management actions. The climate module covers the main climatic variables (Figure 2) that are expected to act as drivers on species or functional groups in the food web modules. An important output of the climate module is the generation of high-quality weather data from automatic weather stations that cover the most important ecological gradients (e.g. coast to inland sites). Weather data are used to calibrate spatial and temporal snow models (see Liston and Elder 2006 for an example), as the cryosphere has a key role in determining the dynamics of the Svalbard tundra ecosystem (e.g. Stien et al. 2012; Hansen et al. 2013).

1.3 Conceptual models, monitoring targets, state variables and analyses

Each conceptual model outlines (1) key ecological interactions (trophic or competitive) between monitoring targets, (2) the most likely pathways for impacts of climate change and (3) the options and pathways for management to alleviate or mitigate negative pressure impacts (see Lindenmayer and Likens 2009; 2010a,b; 2011 for description of the use of conceptual models in long-term monitoring). Although climate change is expected to be the main driver of ecological change, other drivers can be locally or regionally important. In the COAT models these local pressures are represented by the management-impact pathways, because local pressures such as harvesting, development of infrastructure and

Box 1. Svalbard terrestrial tundra ecosystem

Compared to many other tundra ecosystems, even in equivalent bioclimatic subzones, the Svalbard food web is relatively simple, and some typical Arctic key-stone species and food chains are missing. The isolated geographical positioning of the archipelago, possibly together with certain attributes of the climate, are main reasons for this. The key herbivore species present are one ungulate (the endemic Svalbard reindeer), one species of ptarmigan (the endemic Svalbard rock ptarmigan) and two species of migrating geese (the pink-footed and the barnacle goose). The predator/scavenger guild is also depauperate with the main species being the Arctic fox and the glaucous gull, the latter being a species that also make extensive use of marine food sources. Indeed, marine subsidies (both in terms of nutrient and energy) to the terrestrial ecosystems are more profound in the coastal areas of Svalbard than in many other High Arctic regions (Ims and Ehrich 2013). Migrating passerines (e.g. snow bunting) and shore birds (e.g. purple sandpipers) add to the species diversity and abundance of prey in the summer season (Kovacs and Lydersen 2006). Contrary to what is found in most tundra food-webs (Ims and Fuglei 2005), small and medium-sized mammalian herbivores (rodents and hares) and specialist predators are functionally absent on Svalbard (Strøm and Bangjord 2004). Only a local introduced population of sibling vole is spatially restricted to the area around a sea bird colony in Grumant, Nordenskiöld Land peninsula (Henttonen et al. 2001). Figure from Ims et al (2013).



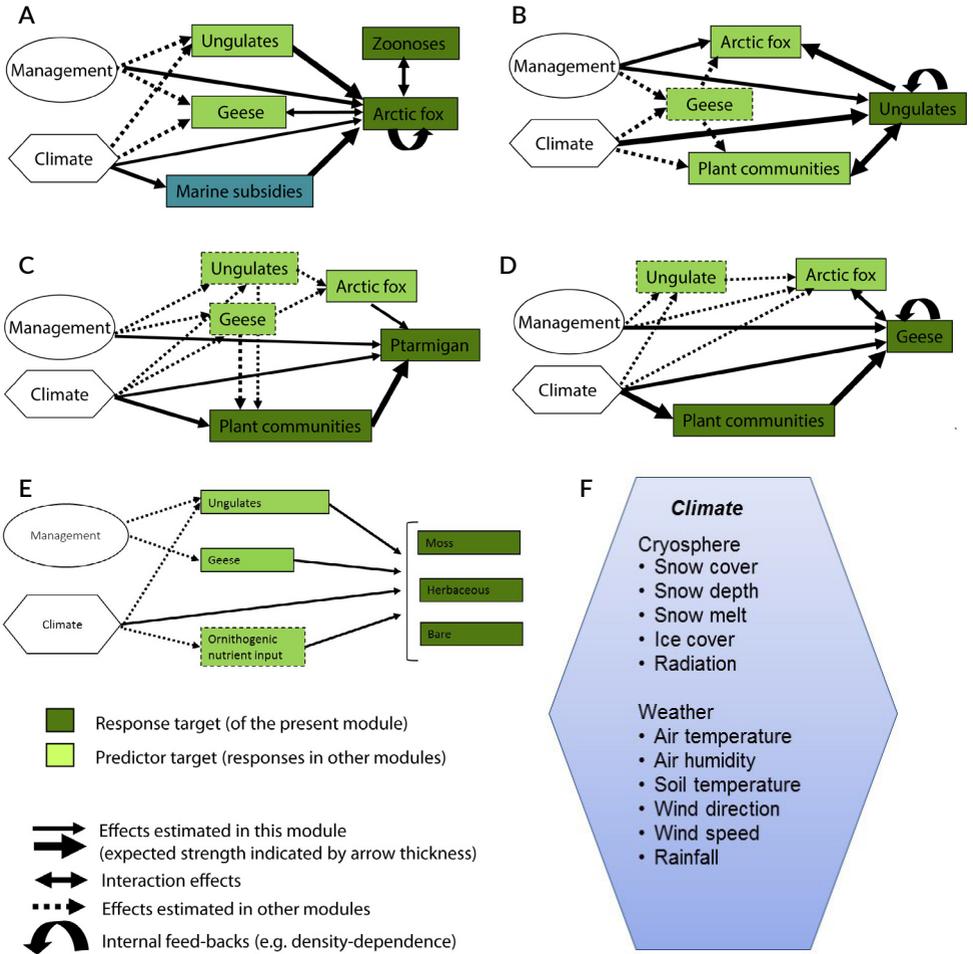


Figure 2: The conceptual models representing the five food web modules and the climate module of COAT Climate - ecological Observatory for Arctic Tundra (after Ims et al. 2013). Each model specifies climate and management impact pathways on prioritized monitoring targets. A. Arctic fox module, B. Reindeer module, C. Ptarmigan module and D. Goose module, E. Moss tundra module and F. Climate module, including the main climate state variables that are relevant to the monitoring components in the food web modules. See Box 2 for a summary of key attributes for each conceptual food web module.

increased traffic in principle can be dealt with by appropriate local management actions (Figure 2 and Box 2). Furthermore, monitoring targets that are subject to management actions are prioritized in COAT. Additional criteria for inclusion as a monitoring target were high climate sensitivity, high importance as conservation targets (e.g. endemic species) and high usefulness for comparative scientific analysis in a circumpolar context.

Box 2. Key attributes and motivations behind the five food-web modules

The Arctic fox model (Figure 2A) targets (1) the *Arctic fox* because it is functionally the most important predator within the terrestrial food-web and (2) *Arctic fox parasites* and *diseases* that represent dangerous zoonoses (rabies, toxoplasmosis and parasites) for humans. Management options and local pressures are harvesting and regulating traffic. Potentially important climate impact paths are change of herbivore abundance and changing sea ice extent. Additionally, the Arctic fox is the terrestrial species most subjected to bioaccumulation of long-distance transported pollutants.



The reindeer model (Figure 2B) targets the *Svalbard reindeer* and (2) *plant communities* containing the main forage plants. The endemic Svalbard reindeer have increased in abundance and expanded their spatial range (Le Moulllec 2019). Recent studies have revealed direct sensitivity of the reindeer to climate (Hansen et al. 2011; Hansen et al. 2013; Hansen et al. 2019a). The reindeer has a key role in *plant community* dynamics (see van der Wal et al. 2001; van der Wal et al. 2004) and a strong influence on the population dynamics of the Arctic fox (Eide et al. 2004). Management options and local pressures are recreational hunting.



The ptarmigan model (Figure 2C) targets (1) the *Svalbard rock ptarmigan* and (2) *plant communities* containing the main forage plants. The key climate-impact pathway affecting ptarmigan is predicted to be indirectly mediated by phenological changes in food plants and reproduction (Henden et al. 2017; Beard et al. 2019). Management options and local pressures are recreational hunting. In a conservation perspective, the Svalbard ptarmigan is an endemic sub-species that appears in low, but increasing densities, which contrast most other ptarmigan populations (Fuglei et al. 2019).



The goose model (Figure 2D) targets (1) the two goose species (*pink-footed* and *barnacle goose*) and (2) the *plant communities* they interact with. Geese have high impact on Arctic plant communities (e.g. Abraham et al. 2005; Speed et al. 2009; Madsen et al. 2011), their important interactions with the Arctic fox that determines their breeding success (Layton-Matthews et al. 2019b), as well as the many issues that relate to the management of long-distant migrants. Management options are hunting on flyways and wintering grounds (Madsen and Williams 2012).



The **moss tundra model** (Figure 2E) targets moist moss tundra that can occur in 3 alternative states; a *thick moss layer*, *herbaceous plant dominated* and *bare patches* and focuses on the transitions between these states (Ravolainen et al. 2019). The key climate-pathway is predicted to be warm summer temperatures that can be indirectly mediated by increased abundance of herbivores leading to shifts in vegetation states via grazing, trampling and fertilization, and by nutrient input from seabirds and geese. The module also monitors *Dryas octopetala* vegetation, changes caused by winter damage and permafrost processes, and comprises a landscape scale remote sensing component.



Each of the conceptual models is further detailed by sets of *state variables*. While the *monitoring targets* are broad categories of interest (Figure 2 and Box 2), the state variables are the specific aspects of these monitoring targets that are sampled at relevant spatial and temporal scales, e.g. abundance, mortality, reproduction, body mass and demography (for a complete list see Ims et al. 2013). Many monitoring targets are involved in several conceptual models, often as a response target in one conceptual model while being a predictor target (driver) in other models (Figure 2). This affects the sampling designs for targets; each target has to be sampled at a temporal and spatial scale that is suitable for all the ecological processes it is involved in. Climate affects several processes in all the conceptual models. This implies that many state variables describing climate have to be sampled using an intensive study design, and at spatial scales appropriate for evaluating monitoring targets. For example, vegetation changes need to be monitored using a fine-scale spatial sampling design. To understand how climate affects vegetation, monitoring of climate state variables related to vegetation requires a study design that matches the vegetation sampling localities and spatial scale. Regarding temporal scaling, the timing of certain events requires simultaneous monitoring data with high temporal resolution across several trophic levels (cf. example of trophic mismatch below). To facilitate data-driven causal analyses and predictions the conceptual models of COAT need to be translated into statistical models. Indeed, a key purpose of the formulation of the conceptual models is to define the structure (the skeleton) of dynamical structural equation models (Grace et al. 2016). These statistical models will be analysed to both identify causal relations and provide short-term predictions (Ims et al. 2013).

1.4 Adaptive monitoring for understanding novel ecosystem processes

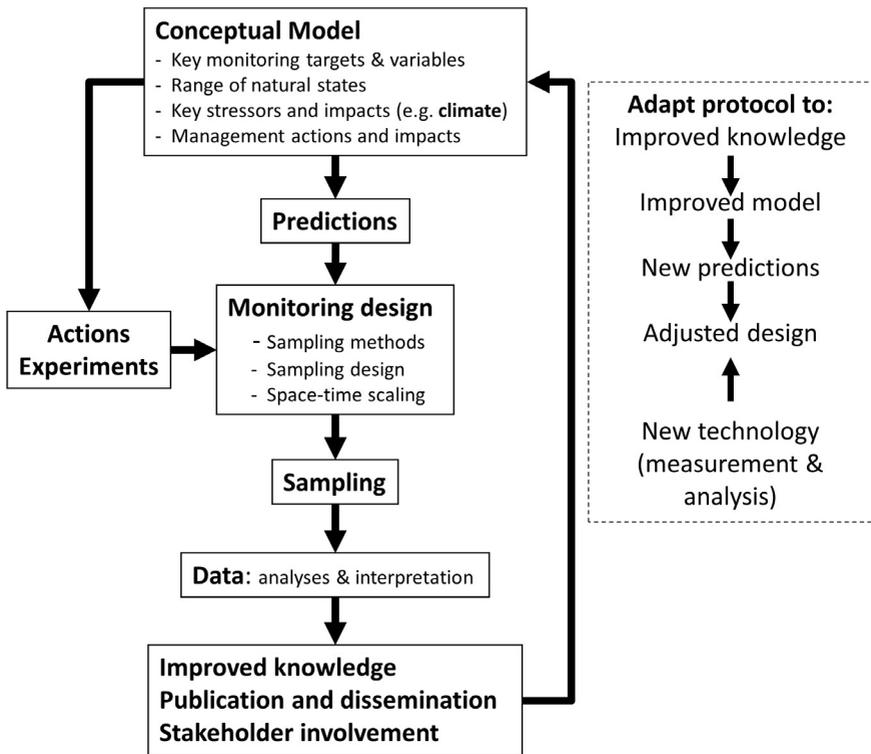
Ecological monitoring programmes need to be driven by questions and hypotheses of causality to be powerful tools for scientific inference and management decisions (Yoccoz et al. 2001; Legg and Nagy 2006; Nichols and Williams 2006; Lindenmayer and Likens 2009; Lindenmayer and Likens 2010b). In COAT, the conceptual models formulate these hypotheses. COAT further sets the conceptual models in an adaptive monitoring protocol framework (Lindenmayer and Likens 2009) (Box 3). This framework allows for a robust hypothetico-deductive approach that combines observational time-series of state variables (e.g. key climatic drivers such snow cover and temperature and food web response variables). The overall aim of the adaptive protocol is to attain increased knowledge of the effects of climate change on food web interactions and inference of optimal and adaptive management interventions in novel and unpredictable environments. An active interphase with management and stakeholders is implicit in the framework and is integral to understanding ecosystem functioning. Through the project SUSTAIN¹, COAT currently

1 www.sustain.uio.no/

Box 3. Design protocol for monitoring the COAT Svalbard tundra ecosystem.

Adaptive monitoring - a design for long-term, real-time monitoring in rapidly changing and novel environments.

Food-web dynamics are represented by conceptual models (Figure 2) describing the direct and indirect links between key drivers (climate and management), and key monitoring targets (species, communities, functional guilds) anticipated to reflect the functioning and structure of the tundra ecosystem. Predictions of relationships between monitoring targets and drivers are set by *a priori* hypotheses. Hypotheses are tested via experimental manipulations or by using observational study design. This results in understanding of the effectiveness of management actions and climate impacts on monitoring targets. Hierarchical multi-scale (both temporal and spatial) sampling design allows discrimination between changes of monitoring target caused by external drivers and internal processes. Sampling is undertaken, followed by analyses and interpretation of resulting data. We particularly focus on short-term predictions or forecasts that can be compared with observations. The resulting improved knowledge of food-web interactions are discussed with stakeholders (including management) and disseminated to the public. The protocol is adapted as necessary and the steps are reiterated to allow long-term adaptive management of the ecosystem component to mitigate adverse effects of climatic change on the Svalbard tundra ecosystem. COAT thus follows the adaptive monitoring protocols by (Lindenmayer and Likens (2009).



investigates the utility of a Strategic Foresight Protocol as a vehicle for providing such an active interphase between ecosystem science and end-users (Ims and Yoccoz 2017)

2. Current status and trends in the Svalbard terrestrial ecosystem

In this section, we give a brief summary of status and trends in monitoring targets and processes described in the conceptual climate impact path models. We mainly review the results from monitoring targets for which long time series are available and present hypotheses and predictions (i.e. expressed in the conceptual COAT models; Figure 2) that will be tested in future analyses when adequate data have become available.

2.1 Climate characteristics and ecological implications

There have been several recent reviews of Svalbard's current climate and trends therein (e.g. Gjeltten et al. 2016; Isaksen et al. 2016; Vikhamar-Schuler et al. 2016; Renner et al. 2018; Hanssen-Bauer et al. 2019; IPCC 2019). Below we summarize the main conclusions and give a brief summary of expected ecological implications.

Temperature has increased (3 – 5 ° C between 1971 and 2017) in all seasons - with the largest increase in winter and the smallest in summer (Figure 3A) (Isaksen et al. 2016; Hanssen-Bauer et al. 2019). The winters are milder and characterized by fewer cold winter days (Gjeltten et al. 2016) and more days with precipitation falling as rain (Figure 3B). Warmer July temperatures (Figure 3C) signal a change in characteristics of the plant growing season and July temperature is therefore a key indicator of a climatic region, and the basis for the climatic delineation of the Arctic bioclimatic subzones (CAVM Team 2003). Changes in mean July temperature on Svalbard indicate that climatically, the majority of the Svalbard tundra has shifted an entire bio-climatic sub-zone (Figure 3C) (Vikhamar-Schuler et al. 2016; Jepsen et al. 2019). Climatic change in these zones is expected to be accompanied by significant alteration of ecosystems and focal components with knock-on effects on function, structure and productivity (IPCC 2019).

Higher temperatures have led to winter rain becoming more frequent (Figure 4a), resulting in a regime shift in winter climate. Both the spatial occurrence and thickness of basal ice increased strongly with the annual amount of winter rain (Peeters et al. 2019). However, considerable spatial variation exists (Figure 4b), particularly along gradients from coast to inland (Peeters et al. 2019). Increased frequency of rain-on-snow, resulting in basal ground ice formation has negative impacts on population growth rates of the winter resident species of the vertebrate animal community (Stien et al. 2012; Hansen et al. 2013). Basal ground ice damages vegetation (Milner et al. 2016; Bjerke et al. 2017) and prevents

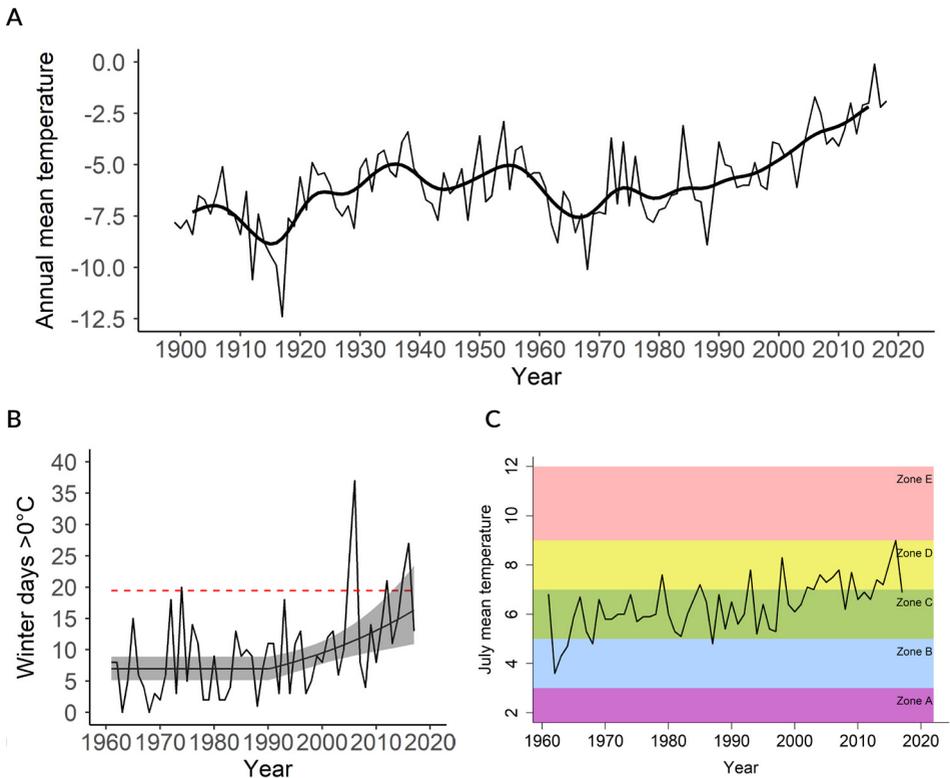


Figure 3: A: Observed trends in annual temperature in the Svalbard terrestrial tundra ecosystem. Mean annual temperature at Svalbard Airport meteorological station (1899–2018). The thick black line shows the long-term variability at the decadal scale (Nordli et al. 2014; Isaksen et al. 2016). B: The number of winter days (daily mean temperature > 0°C), for Svalbard Airport meteorological stations (1961–2017). The rate of change, relative to the 1961–1990 normal period, is shown with $\pm 2SE$ and the dashed red line indicates 2SD of variation observed in the normal period 1961–1990 (modified from Jepsen et al. 2019). C: The mean July temperature of Svalbard Airport meteorological station (1961–2017) against the climatic boundaries of the Arctic bioclimatic subzones. After year 2000, this part of Svalbard has, climatically, shifted from subzone C (Middle Arctic tundra Zone) to subzone D (Southern Arctic Tundra Zone) (modified from Jepsen et al. 2019).

herbivores accessing food. Increased winter mortality of Svalbard reindeer in turn affects food availability for the Arctic fox (*Vulpes lagopus*) (Eide et al. 2012). It is still unclear whether the winters have become so mild that they make forage more accessible (due to snow melting) rather than locking away access to foraging grounds (due to ground ice formation).

Hydrological characteristics are changing due to increased precipitation and snowmelt patterns (see Gallet et al. 2019 for a review). The annual average surface run-off has increased by more than a third, mainly due to increased glacier melt and increased winter precipitation. This may increase glacial lake outburst floods as well as affecting erosion

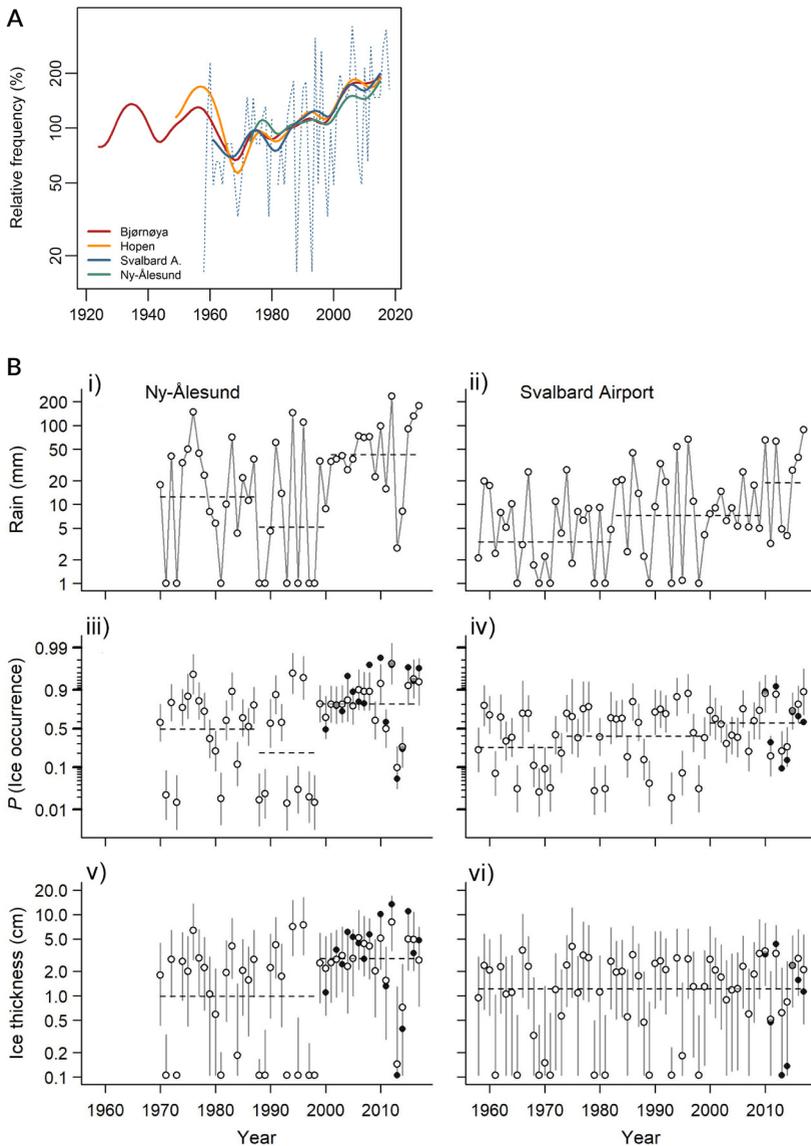


Figure 4: Observed trends in precipitation and ice characteristics of the terrestrial Svalbard. A) number of days per year relative to the 1971-2000 average of observed precipitation and a daily mean temperature over 0°C (Hanssen-Bauer et al. 2019); B) Regime shifts in rain and basal ground ice: Historical amounts of winter rain (i - ii) and past modelled basal ground ice occurrence (iii - iv) and basal ground ice thickness (v - vi). Data from two meteorological stations: Ny-Ålesund, NW coast (i, iii, v) and Svalbard Airport, central Spitsbergen (ii, iv, vi). Average observed values up to 200 m elevation are included as black dots (or grey when overlapping with model estimates). Horizontal dashed lines indicate average values before and after observed regime shifts (i) 1987, 2000, (ii) 1982, 2009, (iii) 1987, 1998 (iv) 1973, 1999 (v) 1998 (vi) no change point observed (Peeters et al. 2019).

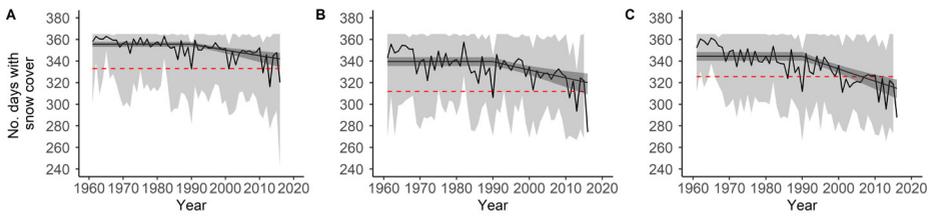


Figure 5: Number of days with snow cover for the three bioclimatic subzones Arctic Polar Desert Zone (A), Northern Arctic Tundra Zone (B) and Middle Arctic Tundra Zone (C) (extracted from Østby et al. 2017). The rate of change, relative to the 1961–1990 normal period, is shown with 2.5% – 97.5% confidence intervals. The dashed red line indicates 2SD of variation observed in the normal period (modified from Jepsen et al. 2019).

intensity and sediment supply to rivers (Hanssen-Bauer et al. 2019). The snow season has decreased by approximately 20 days since the middle of the last century and this trend is expected to continue decreasing, resulting in shifts in spring- and winter onset (Hanssen-Bauer et al. 2019). Snow cover duration is decreasing everywhere in the High Arctic, but most rapidly in the Middle-Arctic Tundra Zone (subzone A) (Jepsen et al. 2019) (Figure 5).

Changes in season length have a range of implications for food web interactions. Earlier springs may lead to phenological mismatch between egg laying and food resources for Svalbard rock ptarmigan (*Lagopus muta hyperborea*) (Ims et al. 2013; Wann et al. 2019), but data on this are still not available. Alternatively, an extended grazing season may have a positive effect on reproduction and habitat suitability for herbivores (Jensen et al. 2008; Albon et al.

2017; Layton-Matthews et al. 2019b; Rivrud et al. 2019). Furthermore, patterns of snow melt may determine the extent and intensity of disturbance of the tundra by geese grubbing

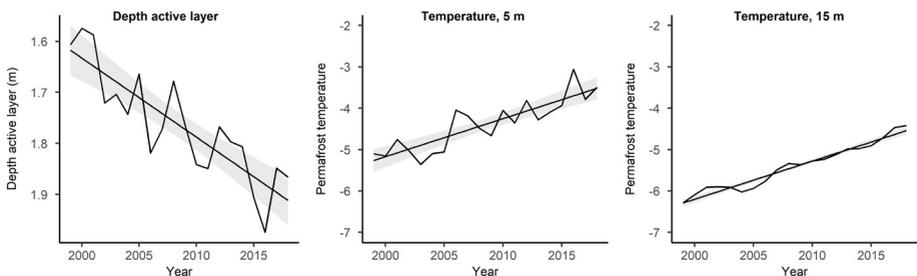


Figure 6: Trends in depth of the active layer (left) and permafrost temperatures (Sept. 1st) at 5 meters (middle) and 15 meters (right) depth in Adventdalen in central Spitsbergen (Isaksen pers. comm.: www.mosj.no). Trend lines indicate the estimated linear rate of change and shading indicates $\pm 2SE$ (modified from Jepsen et al. 2019).

for belowground food items in early spring (Pedersen et al. 2013b; Pedersen et al. 2013c; Anderson et al. 2016) and breeding success (Madsen et al. 2007; Jensen et al. 2014).

Increased air temperature and precipitation are resulting in an annual reduction in permafrost depth in High Arctic Svalbard (Hanssen-Bauer et al. 2019). This leads to an associated increase in annual and seasonal temperature of permafrost layers and active soil layer (Isaksen et al. 2007; Etzelmüller et al. 2011) (Figure 6), which in turn can increase instability of slopes, hydrology and vegetation, especially where permafrost layers exist in sediments (Hanssen-Bauer et al. 2019).

Sea ice reductions are most pronounced in Svalbard and the Barents Sea area (Onarheim et al. 2018). The loss of sea ice and the earlier retreat in spring also have implications for the terrestrial ecosystem. The retreat in spring has on average been two weeks earlier per decade since 1979 (Laidre et al. 2015). Whereas the local/sub-regional component is attributed to sea breeze (cold air advection from ice-covered ocean onto adjacent land during the growing season), the large-scale component might reflect co-variability of sea ice and tundra productivity due to a common forcing (North Atlantic Oscillation) (Macias-Fauria et al. 2017). In addition, sea ice loss reduces the possibilities for Arctic fox hunting and scavenging on this substrate (Gaston et al. 2012; Fuglei and Tarroux 2019) and reindeer movement (Hansen et al. 2010).

These changing climatic conditions have a profound effect on the state of the cryosphere, which in turn determines the timing and extent of the growing season and the available resources for plants and animals. The snowscapes of Svalbard are highly heterogeneous, due to steep climatic gradients from coast to inland and a complex topography. Hence the monitoring design for measuring climate state variables needs to capture this variation. The COAT automated weather stations that will be in place within 2021, combined with field observations and experiments are essential to measure a suite of state variables necessary to predict and forecast effects from climate change on the Svalbard tundra food web. Such measures will be strengthened and complemented by additional remote sensing and ground based measurements of the cryosphere. The fine scale meteorological data will be used to calibrate landscape-scale snow models to improve our understanding of climate change on biotic processes in the tundra ecosystem.

2.2 Primary productivity

An increase in the temperature on Svalbard has led to increased primary production as measured by plant biomass (van der Wal and Stien 2014). Individual plants across habitats, plant functional types and species grow better in warm summers (van der Wal and Stien 2014; Milner et al. 2018; Le Moullec et al. 2019) given sufficient moisture (Elmendorf et al.

2012). However, satellite-based measures of plant biomass, which use the plant productivity index NDVI is more difficult to use in Svalbard than elsewhere due to frequent cloud cover. Different studies have adopted different approaches and this has led to conflicting conclusions regarding the validity of a link between NDVI and plant biomass (Johansen and Tommervik 2014; Vickers et al. 2016; Karlsen et al. 2018). However, the high-resolution spatial layers mapping plant productivity from Sentinel-2 data may be a key to disentangle some of the current issues observed ([Karlsen et al. 2020](#)).

Vegetation productivity is influenced by multiple abiotic and biotic factors. Experimental studies from Svalbard show plant growth responses to ice- and frost damage in the winter (Milner et al. 2016). Furthermore, herbivores may affect the vegetation negatively through grazing, trampling and grubbing (Van der Wal and Brooker 2004), but also have more indirect effects through increased fertilization and nutrient recycling (Ravolainen et al. 2019). The main grazers on Svalbard have both increased in population size in recent decades (Le Moullec et al. 2019; Figure 7). Finally, seabirds have a fertilising impact on vegetation, bringing nitrogen of marine origin into the terrestrial ecosystem (Zwolicki et al. 2013; Zwolicki et al. 2016).

The moss tundra vegetation presently functions as a hotspot of primary production and herbivore diversity. Direct climate effects as well as indirect effects from changes in abundance of herbivores and seabirds may cause a change from a moss dominated slow nutrient cycling system to herbaceous dominated faster nutrient cycling system. The moss tundra vegetation module will use a combination of field- and remote sensing monitoring techniques to provide data for estimating direct and indirect effects of climate on vegetation (Ravolainen et al. 2019).

2.3 Changes in higher trophic levels

2.3.1 Reindeer

Svalbard reindeer (*Rangifer tarandus platyrhynchus*) are key herbivores in the Svalbard tundra ecosystem, maintaining grass communities in an otherwise moss dominated ecosystem (Van der Wal and Brooker 2004). The reindeer population lacks influential predators and insect harassments, and harvest is strictly regulated to such low levels that it is not expected to affect population dynamics. Reindeer abundance on Svalbard has increased two-fold during the last decades (Le Moullec et al. 2019). However, monitored coastal and inland populations have contrasting trajectories (Hansen et al. 2019b; Le Moullec 2019). The population on the Nordskiöld Land peninsula has increased, while the population on the more northerly Brøggerhalvøya has remained stable at lower abundance levels (Hansen et al. 2019b). The Svalbard reindeer populations show large annual fluctuations in numbers but appear to be spatially synchronized by annual winter weather variability (Aanes et al. 2003;

Stien et al. 2012; Hansen et al. 2019b).

Long-term individual based studies of the population in Nordenskiöld Land peninsula have given insight into the mechanisms of the drivers of population dynamics - with contrasting effects of summer and winter climate determining the population trend. When summers and autumns are warm, reindeer body masses are higher in the autumn and even in the following spring, likely associated with higher plant productivity and extended grazing seasons (Albon et al. 2017). However, reindeer body mass is during the spring strongly influenced by rain-on-snow events, which also determine vital rates and ultimately variability in population growth rates (Albon et al. 2017). In winters with extensive basal ground ice, larger numbers of reindeer die, mainly through increased mortality of the youngest and oldest individuals, when the population is at high densities (Stien et al. 2012; Hansen et al. 2013). Recent analyses of long-term data sets of biological and weather state variables show that more frequent rain-on-snow events reduce extinction risk and stabilize population dynamics at lower levels due to interactions between age structure and density dependence (Hansen et al. 2019a).

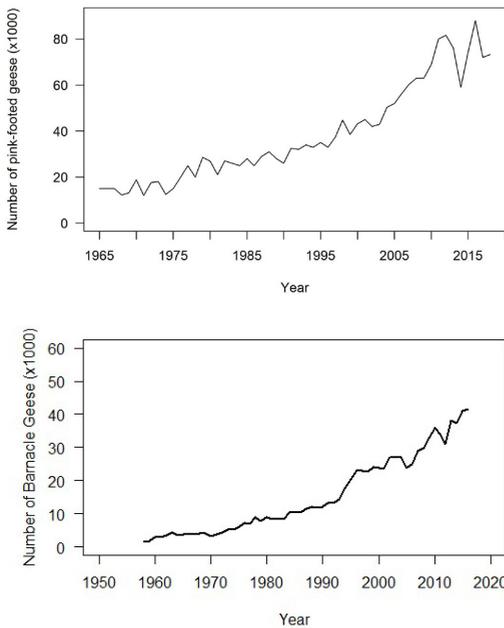


Figure 7: Left panel: Population size of pink-footed goose (upper) and barnacle goose (lower) in Svalbard. Goose counts are carried out on their wintering grounds in the UK (modified after Jensen et al. 2018; Johnson et al. 2018). Right panel: Impacts of intense pink-footed goose grubbing. Photo: Jesper Madsen.

Reindeer can have local effects on plant biomass. Further, they also modify the tundra vegetation communities (van der Wal et al. 2001; Van der Wal and Brooker 2004), and changes in reindeer abundance are expected to have knock on effects on composition, structure and productivity of the Svalbard tundra. Currently, there is lack of information on potential resource competition with geese, although the numbers of both species are increasing. Furthermore, the changing dynamics of rain-on-snow events are likely to play a large role in constraining the abundance and population growth rates of reindeer (Hansen et al. 2019a).

2.3.2 Svalbard rock ptarmigan

The Svalbard rock ptarmigan is an endemic sub-species restricted to Svalbard and Franz Josef Land. It is the only resident herbivore bird in the tundra ecosystem (Løvenskiold 1964), and the most important predator is the Arctic fox (Steen and Unander 1985). Currently, they are subject to local harvest (Soininen et al. 2016). Annual monitoring of spring densities of territorial males reveals low abundances (1-3 males per km²) with moderate temporal fluctuations and no significant linear trends for the period 2000-2013 (Pedersen et al. 2012; Soininen et al. 2016). However, since 2014 the spring density has increased and reached a density level between 3-5 males per km² with a current positive trend (Fuglei et al. 2019). The temporal fluctuation in spring densities is partly driven by inter-annual variation in rain-on-snow events with population reductions in years with high occurrence of winter rain (Hansen et al. 2013). The monitoring data indicate an increasing trend in spring density, however, hunting statistics (i.e. bag size and the proportion of juveniles in the bag), show the opposite trend (Soininen et al. 2016). The discrepancies between these time-series are currently under interpretation. The Svalbard rock ptarmigan has limited amount of suitable breeding habitats available (< 4 %), which is also suggested to be one limiting factor for the breeding population (Pedersen et al. 2017).

Svalbard rock ptarmigan is predicted to be both directly and indirectly impacted by climate change (Ims et al. 2013; Henden et al. 2017). Rain-on-snow events, have already been shown to have direct negative effects on the population growth rate (Hansen et al. 2013). Moreover, increased weather variability in spring and summer is predicted to affect the onset of breeding and chick survival (Ims et al. 2013). Newborn ptarmigan chicks have a highly specialized diet of *Bistorta vivipara* bulbils (Unander et al. 1985). This is likely to make them vulnerable to phenological mismatch with their preferred food plants (Ims et al. 2013). A warmer summer climate may have a positive effect on the ptarmigan population through increased plant productivity, but warmer, icy winters that cause widespread damage to especially *Dryas* vegetation (Milner et al. 2016; Bjerke et al. 2017) that ptarmigan rely on in the spring, may have negative effects. The increasing populations of pink-footed geese may have a negative impact on ptarmigan forage resources through their intensive grazing and grubbing that remove important food plants (Ims et al. 2013).

2.3.3 Geese

Geese are key herbivorous species in the Svalbard tundra ecosystems, even though they are seasonal migrants spending just four months of the year in the archipelago (Madsen et al. 1999). All three species (pink-footed goose, barnacle goose and brent goose; *Branta bernicla*) have increased in recent years, but barnacle and pink-footed geese have seen the biggest increases (Clausen and Craggs 2018; Jensen et al. 2018; Madsen et al. 2018). The increases are due to a combination of increased overwintering survival due to increased protection from hunting and changed agricultural practices along their flyways (Johnson et al. 2018).

Svalbard geese are directly affected by changes in climate, as earlier snowmelt allows earlier nesting, and leads to increased nesting success (Madsen et al. 2007; Jensen et al. 2014; Layton-Matthews et al. 2019b). The climatically driven changes are likely to allow goose population densities to increase and distributions to expand (Jensen et al. 2008; Wisz et al. 2008). Particularly, the spring foraging by pink-footed geese (grubbing) has resulted in the changes of vegetation community composition, structure and function (Kuijper et al. 2006; van der Wal et al. 2007; Pedersen et al. 2013a). Grubbing leads to destruction of roots and rhizomes of food species and adjacent moss carpets concentrated in the fen regions (Fox et al. 2006). Multi-annual grubbing hampers regeneration and the removal of large amounts of plant material can have knock on effects for net ecosystem change (van der Wal et al. 2007). Removal of moss and trampling modifies the vegetation community, leading to increased soil temperature and enhanced graminoid growth (van der Wal et al. 2000; Gornall et al. 2009). However, vegetation degradation appears to be moderated by inter-annual variation in snowmelt patterns that structure grubbing activity (Anderson et al. 2016).

Arctic fox feed on geese, and can regulate goose population growth by predation of goslings (Eide et al. 2004; Madsen et al. 2007; Anderson et al. 2019; Layton-Matthews et al. 2019a). Barnacle geese are also vulnerable to egg predation by polar bears (*Ursus maritimus*) (Prop et al. 2015). The increasing populations impact negatively on the Svalbard rock ptarmigan population through the geese's removal of the tundra vegetation (Ims et al. 2013) or positively by a reduction in predation compatible with apparent mutualism and/or prey swamping mechanisms (Pedersen et al. 2018).

2.3.4 Arctic fox

Arctic fox is the only terrestrial mammalian apex predator and scavenger in the tundra ecosystem (Eide et al. 2004; Eide et al. 2005). It links the terrestrial food web to subsidies from the marine food web through prey, such as sea birds and seal carcasses (Prestrud 1992; Ims et al. 2013). Because Svalbard lacks cyclically fluctuating small rodents like lemmings, the Arctic fox population belongs to the coastal ecotype. Stable resources from the marine ecosystem subsidize this type, and population levels are generally more stable

compared to other types of Arctic fox populations in the Arctic. It is also an important carrier of zoonoses (animal born parasites/diseases that may spill over to humans) (Sørensen et al. 2005; Prestrud et al. 2007; Mørk et al. 2011).

The monitored Arctic fox populations show considerable annual variation in abundance, but the long-term population abundance trend is stable to slightly increasing, although they are locally trapped in parts of the monitoring areas (Eide et al. 2012; Layton-Matthews et al. 2019a). Their population dynamics are likely to be affected both directly and indirectly by climate. Arctic foxes may be indirectly negatively affected by the reduced availability of marine prey in the winter due to reduced sea ice cover that is habitat for important prey species, e.g. ringed seal (Tarrowx et al. 2012), and in the summer due to the collapse of some seabird colonies (Descamps et al. 2013; Descamps et al. 2017). The Arctic fox abundance and reproduction is positively related to the amount of reindeer carcasses on the tundra (Eide et al. 2012; Hansen et al. 2013). However, this results in a one-year delayed negative impact on the population growth rate of foxes after severe winters (Hansen et al. 2013). Additionally, a warmer spring and summer has a positive influence on the amount and breeding success of geese (Madsen et al. 2007; Jensen et al. 2014), with likely subsequent positive effects on Arctic fox population dynamics (Ims et al. 2013). Winter sea ice allows dispersal, migration, and interchange of genes between the Svalbard population and other circumpolar ranges (Ehrich et al. 2012; Fuglei and Tarrowx 2019). Thus, the reduction in sea ice extent (Gaston et al. 2012) may have consequences for population structure, robustness and long-term viability of the Arctic fox populations (Fuglei and Tarrowx 2019).

2.4. Overall trends in monitoring targets

Currently abundance of monitored vertebrate populations appears to be stable or increasing for reindeer, ptarmigan, fox and geese (Jensen et al. 2018; Fuglei et al. 2019; Hansen et al. 2019b; www.mosj.no). There could be several reasons for this. The herbivores in the food webs that are monitored involve resident and migratory species that are at the northern edge of their range. They are adapted to harsh conditions, i.e. food limitation and extreme cold, but show considerable plasticity so that improved carrying capacity of the tundra during the summer season allows for better condition, and hence increased reproduction. Stochastic perturbations in the form of large-scale rain on snow, causing ground ice is still impacting annual variability in population growth rate, but the timing, scale and frequency of such impact may no longer be as severe as earlier described (Hansen et al. 2013), perhaps because improved conditions during the summer have increased the resilience of individuals to the severe weather events in winter. Recently, Hansen et al. (2019a) documented that such severe events have a temporary stabilizing effect on population size of reindeer rather than negative effects. Tundra plants respond immediately to increased summer temperature by increased growth (Van de Val and Stien 2014), but as of yet we are unable to quantify

the expected bottom-up effects of increased plant growth on higher trophic levels in the food web. While there has been a shift in bioclimatic sub-zone towards a Low Arctic climatic zone, therefore providing a growth season suitable for a higher diversity of plants and with a potential for establishment of other functional groups (e.g. shrubs), any change at plant community level is so far not apparent. This may be due to the fact that there may be long time-lags in such vegetation community level responses. However, there is presently a lack of long-term monitoring data to document community level transitions in vegetation types that may be particularly prone to such transitions and the eventual cascading impacts this may have on food web dynamics and ultimately overall ecosystem function. COAT aims to fill such gaps by establishing the required long-term monitoring and model-based analyses for disentangling changes in key food web processes and thereby provide a better understanding of how climate change impacts High Arctic tundra ecosystems.

3. Challenges and recommendations for the future

Long-term monitoring is instrumental for environmental conservation, management and policy making to (1) establish how various anthropogenic pressures affect the environment and to (2) assess the effectiveness of management actions. However, from originally being an activity initiated and governed by environmental management bodies and policy makers, environmental monitoring has now become a distinct scientific discipline (Lindenmayer and Likens 2009, 2010a, 2010b; Lindenmayer et al. 2011). The World Meteorological Organization (www.public.wmo.int/en) directs its attention to the aspects of climate variability and change that impact the environment. The observational data of weather and climate that are collected through the networks of observing, data-transmitting and forecasting systems, keep policy-makers informed about the state of the environment so that they are in a better position to prevent its further degradation.

In this context, research infrastructures are instrumental to the state variable monitoring of the multiple aspects of climate change and its impacts. Addressing complex issues requires a holistic ecosystem- based adaptive approach, achieved through integration of relevant biotic and abiotic measurements at appropriate spatial and temporal scales with clearly defined goals and targets for monitoring (Haase et al. 2018; Musche et al. 2019). Several key priorities for the development of research infrastructures have recently emerged. These relate to for instance interoperability among different research infrastructures by developing standard measurements of state variables, co-location of measurements at ecological relevant spatial and temporal scales, harmonizing methods, and establishing both methods and tools for data integration, including observation, experiments and modelling (Musche et al. 2019).

The COAT monitoring system, including the field infrastructure is currently under implementation at the core of the SIOS land module. This offers opportunities for

co-location of research infrastructure and state variable measurements at similar scales, as well as production of common data products and models.

For the infrastructure implementation phase, we have the following recommendations:

Co-location of research infrastructure: Full-scale automatic weather stations are core infrastructure of COAT's climate observation network. Currently, two stations are in place (Janssonhaugen and Reindalspasset) and in total eight stations are planned across the extent of COAT's monitoring areas. They measure a range of abiotic state variables across ecological gradients that are expected to change. Research infrastructure for measurements of other abiotic and biotic state variables ought to be co-located with the COAT weather stations and the corresponding climate-monitoring network. Such co-location is planned within COAT, but to date it mainly includes biotic state variables relevant for COAT food web models. Incorporation of a broader range of abiotic state variables related to snow cover properties, permafrost and energy balance would be beneficial as it will allow for development of joint products relevant to both monitoring of the biosphere and the cryosphere.

Focus on snow: The ecosystem impact of changing snow pack properties in a warming climate is a particularly central theme in COAT and a generally important arena for interdisciplinary research between ecology and geophysics. Besides the co-location of research infrastructure and measurements outlined above, there is a need to develop a data-model fusion system that merges available observational datasets on snow properties with state-of-the-science, high-resolution (1- to 500-meter scale), physically based snow models. The goal of this data-enhancement system is to create accurate, spatially distributed, time evolving, datasets that can be used to better understand relationships between ecosystem processes. Several climate impact pathways formulated by COAT conceptual models are driven by changes in snow cover properties. State-of-the-art monitoring of such pathways is dependent on snow modelling products and joint efforts will contribute to this. Moreover, the development of new ecosystem-relevant synthesis variables from the snow modelling work is needed for COAT's statistical food web models to improve quantitative predictions about climate change impacts on species or functional species groups.

For the long-term running COAT's adaptive monitoring program (i.e. after the initial infrastructure implementation phase is completed in 2021) we have the following recommendations:

New methods and technologies: Ecosystem science has entered an era where new technologies allow for automatic measurements of biotic state variables that are more spatially extensive and temporally highly resolved data than the traditional manual measurements. An important component of adaptive monitoring is to include new methods and instruments that can significantly improve our ability to detect changes and attribute them to drivers. Such new methodological developments also include analytical tools

that aid the assimilation and processing of large amounts of raw sensor data to operative ecological state variables, as well as refined statistical models that can be used for more robust causal inferences and short-term predictions based on these state variables.

Interphase with end-users: It is COAT's ambition to be highly relevant to policy makers and managers. Given the prospects of extreme climate change, Arctic ecosystems are likely to become transformed beyond scientists' current powers to make predictions and managers' abilities to perform mitigations and adaptations. This grand challenge requires more sincere efforts to make the kind of structured interphases between monitoring-based ecosystem science and end-users that are presently tried within COAT (Ims and Yoccoz 2017).

4. Data availability

Integration of the variety of state variables is essential to COAT's ecosystem-based approach and geographically distributed observation network. To achieve this, COAT will use a custom-made data portal. The portal will be directly accessible through COAT's web site, and have both meta- and raw data available. The COAT data portal is currently tested by different types of datasets and will be operational in 2020. COAT data portal describes detailed metadata for each dataset, using formats in compliance with international standards. These metadata are reassessed on a yearly basis to make sure that they describe current practices and that no information is lost because of changes in methods and/or designs. The COAT data portal builds on international metadata standards (DCAT, schema.org-structured data and ISO 19115/CSW) and the digital SIOS infrastructure will be able to "harvest" metadata and state variables from this portal.

Acknowledgements

This work was supported by the Research Council of Norway, project number 251658, Svalbard Integrated Arctic Earth Observing System – Knowledge Centre (SIOS-KC) and Tromsø Science Foundation. We thank Matteo De Stefano for contributing text to the section on data availability, Ingrid M. G. Paulsen for helping with figures and photos, and Inger-Hansen Bauer and Bart Peeters for use of published figures.

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