Climate-Ecological Observatory for Arctic Tundra (COAT) – Adaptive system for long-term terrestrial monitoring

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1. COAT in a ‘nutshell’

The Climate Ecological Observatory for Arctic Tundra (COAT) is a response to urgent international calls for the establishment of scientifically robust observation systems enabling long-term and real-time detection, documentation, understanding and predictions of climate impacts on Arctic tundra ecosystems (Christensen et al. 2020). COAT aims to be a fully ecosystem-based, long-term, adaptive monitoring programme, based on a food-web approach (Ims et al. 2013; Ims and Yoccoz 2017; Appendix 1). The focus is on two Norwegian Arctic regions, the low-Arctic Varanger peninsula and high-Arctic Svalbard, that provide pertinent contrasts in ecosystem complexity, climatic conditions and management regimes. COAT Svalbard is an essential component of the Svalbard Integrated Arctic Earth Observing System (SIOS) and serves to optimise and integrate the ecosystem-based terrestrial monitoring.

In 2016, COAT Svalbard started to implement research infrastructure related to data collection, field logistics and data management solutions. To cover the range of existing variation in climatic and management contexts, the data sampling systems are geographically distributed over Svalbard. Seven full-scale operational weather stations form the core infrastructure, essential for quantifying key climatic variables along a coast-inland gradient (Appendix 2). In addition, 32 herbivore exclosures, networks of camera traps and acoustic sensors, telemetric devices on animals, drones, and networks of small instruments that log climate parameters at the ground level have been established (Figure 1). The COAT programme is now entering the operational phase of the long-term ecosystem-based monitoring.

2. Current status and trends in the Svalbard terrestrial ecosystem

In 2021, the first operational assessment of the ecological condition of Norwegian Arctic tundra ecosystems was conducted by a scientific panel, using core long-term monitoring data from COAT Svalbard and MOSJ (www.mosj.no) and the methodology for *Panel-based Assessment of Ecosystem Condition* (PAEC; Jepsen et al. 2020). The assessment was based on analyses of 34 datasets, supporting 24 indicators unique to the terrestrial ecosystem in Svalbard (Appendix 3).

2.1. Climate characteristics and ecological implications

The Arctic tundra is one of Earth’s largest terrestrial biomes, comprising all terrestrial ecosystems north of the continuous boreal forest. Here, temperatures are rising three times faster than the global average (IPCC, 2021). Since 1971, annual air temperature has increased 3–5°C in all seasons, with the largest increase in winter and the smallest in summer (Hanssen-Bauer et al. 2019). Current winters are characterised by fewer extreme cold days (Nordli et al. 2020) and more frequent mild days with precipitation falling as rain (Figure 2A). Climatic delineation of the Arctic bioclimatic subzones is based on July temperatures, as July temperature is a key characteristic of the plant growing season (Figure 2B). Changes in mean July temperature in Svalbard indicate that climatically, most of the Svalbard tundra has shifted by an entire bioclimatic sub-zone (Pedersen et al. 2021c). The bio-climatic zones are moving eastward in accordance with transport of atmospheric heat and moisture from the Icelandic low and the warm West Spitsbergen current (Hanssen-Bauer 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, 2021).

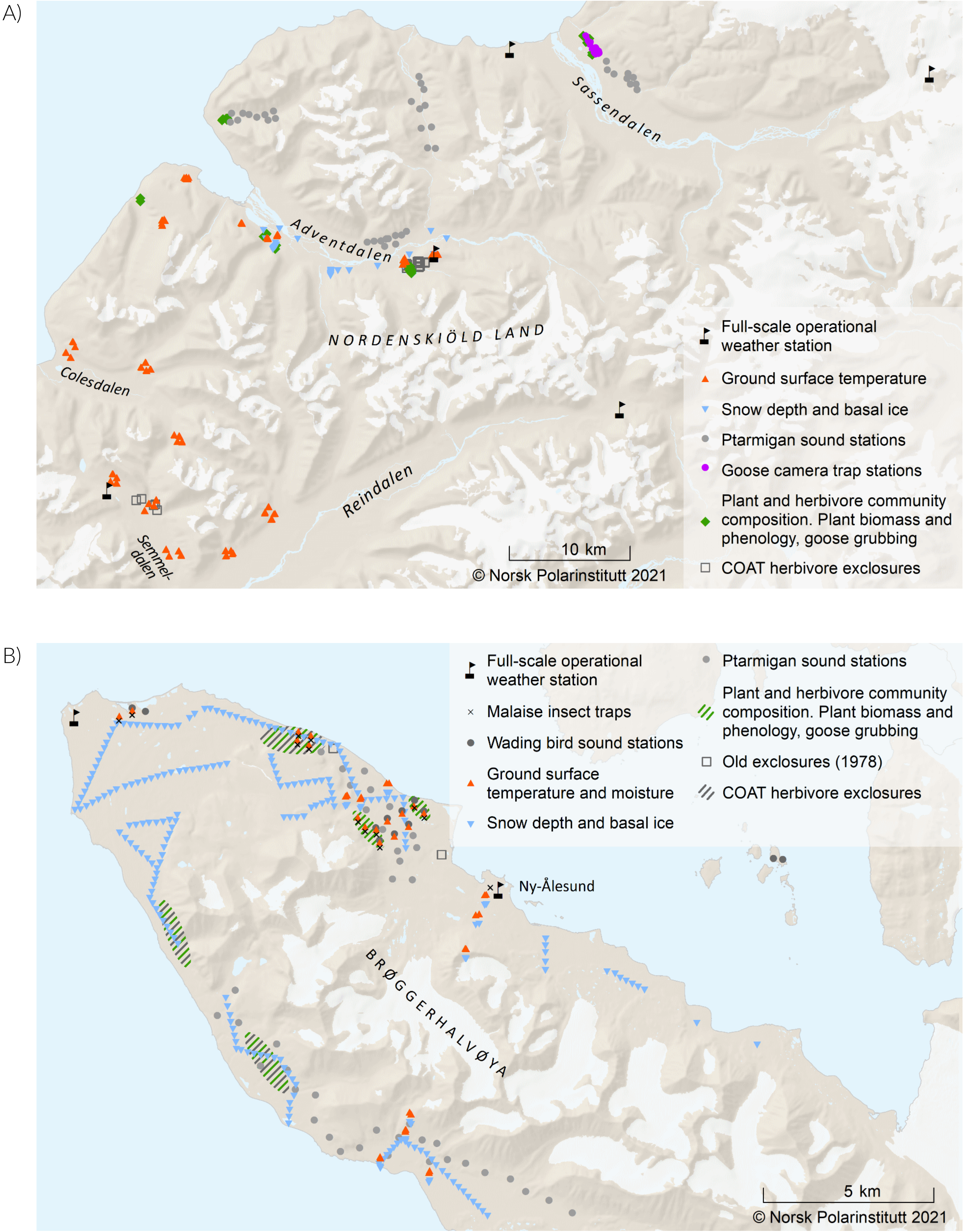

Figure 1: The Climate-ecological Observatory for Arctic Tundra (COAT) builds on and expands the existing monitoring in Svalbard to become fully ecosystem-based. COAT Svalbard is an essential component of the Svalbard Integrated Arctic Earth Observing System (SIOS) and serves to optimise and integrate the ecosystem-based terrestrial monitoring. Currently, COAT Svalbard has implemented research infrastructure in two focal study regions in A) Nordenskiöld Land and B) Brøggerhalvøya. In both these regions there are also existing long time-series on focal ecosystem components like the Arctic fox, geese, Svalbard reindeer and Svalbard rock ptarmigan. (Map: Anders Skoglund, NPI)

For the past 60 years, the measured annual precipitation at the four long-term Norwegian full-scale operational weather stations (Bjørnøya, Hopen, Svalbard Airport, and Ny-Ålesund) in the Svalbard region has increased by 30%–45% (Førland et al. 2020, Figure 2C). Higher winter temperatures cause more frequent episodes of winter rain (Figure 2D), resulting in a regime shift in winter climate (Peeters et al. 2019). The spatial extent and thickness of basal ice increased strongly with the amount of winter rain (Peeters et al. 2019). However, considerable spatial variation exists, particularly along the coast-inland gradient. Increased frequency of rain-on-snow, resulting in basal ground ice formation, has negative impacts on population growth rates of the resident herbivore species (Hansen et al. 2013). Basal ground ice damages vegetation (Milner et al. 2016) and prevents herbivores from accessing food. Increased winter mortality of reindeer, in turn, positively affects food availability for the Arctic fox (*Vulpes lagopus*) and subsequent reproduction (Nater et al. 2021). However, it is still unclear whether increasing temperatures will result in winters so mild that forage access is generally improved for herbivores (due to snow melting), rather than blocking 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 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, resulting in shifts in spring and winter onset (Hanssen-Bauer et al. 2019; Figure 2E). Snow cover duration is decreasing everywhere in Svalbard, but most rapidly in the middle-Arctic tundra zone (Pedersen et al. 2021c).

Changes in season length have a range of implications for food web interactions. An extended growing and grazing season may have a positive effect on reproduction and habitat suitability for herbivores (Albon et al. 2017; Layton-Matthews et al. 2019). Furthermore, patterns of snow melt determine e.g. the extent and intensity of tundra disturbance caused by pink-footed goose (*Anser brachyrhynchus*) when grubbing for below-ground food items in early spring (Anderson et al. 2016) and the subsequent breeding success of migratory geese species (Jensen et al. 2014; Lameris et al. 2019).

The permafrost is thawing, altering landscape structure (Isaksen et al. 2016). Increased air temperatures and precipitation result in an increase in the thickness of the active soil layer above the permafrost in high-Arctic Svalbard (Etzelmüller et al. 2020; Hanssen-Bauer et al. 2019). This is also associated with an increase in the annual and seasonal temperature in the permafrost as well as the near-surface soils within the active layer (Etzelmüller et al. 2020) (Figure 2F). These changes can cause structural instabilities in slopes and in the ground as well as altering hydrology and vegetation, especially where permafrost layers are embedded in sediments (Hanssen-Bauer et al. 2019).

Sea ice decline is pronounced in Svalbard and the Barents Sea area (Onarheim et al. 2018). The loss and earlier retreat of sea ice in spring has implications for the terrestrial ecosystem. In spring, the sea ice has on average retreated two weeks earlier per decade since 1979 (Laidre et al. 2015). Whereas presence of abundant sea ice near the coast during the growing season favours local control of tundra productivity by sea ice, very likely through sea breeze (cold air advection from ice-covered ocean onto adjacent land during the growing season), the large-scale atmospheric and sea surface dynamics (captured by the NAO index) might reflect co-variability of sea ice and tundra productivity (Macias-Fauria et al. 2017). Sea ice loss reduces the possibilities for the Arctic fox to hunt and scavenge on this substrate (Fuglei and Tarroux 2019) and constrains reindeer dispersal (Pedersen et al. 2021b).

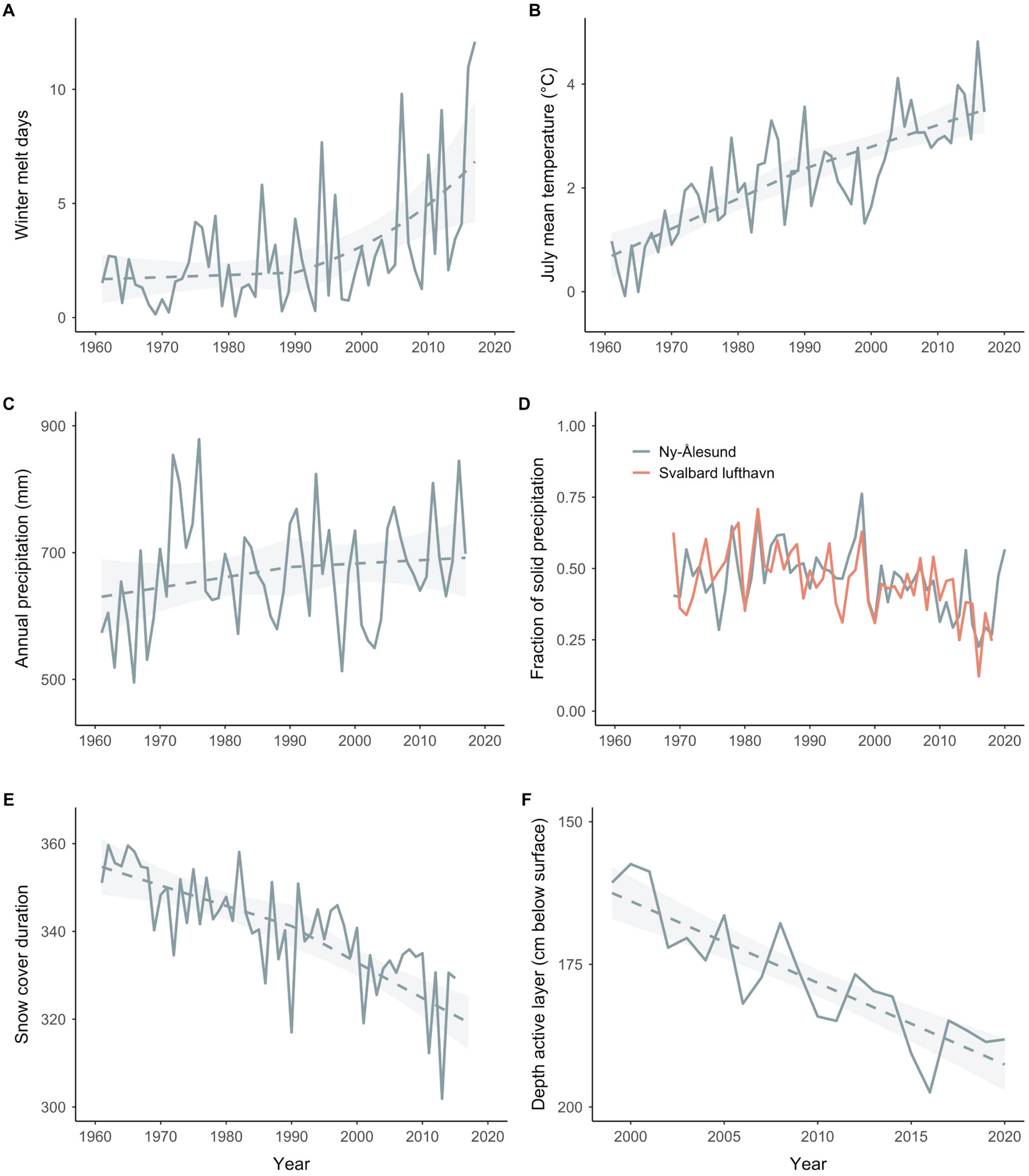

Figure 2: A) Number of winter melt days (daily mean temperature >0°C) per year for Svalbard archipelago, B) modelled annual mean July temperature (°C), C) modelled annual mean precipitation (mm), D) fraction of solid precipitation in Ny-Ålesund and Svalbard Lufthavn during 1969–2018 (modified from Førland et al. 2020), E) modelled number of days with snow cover per year and F) trends in depth (cm) of the active layer in Adventdalen in central Spitsbergen (www.mosj.no). Trend lines indicate the estimated linear rate of change and shading indicates ±2SE (modified from Pedersen et al. 2021b). Data for figure A-C and E are based on 1×1 km gridded datasets derived from downscaling of atmospheric reanalyses (Sval-Imp dataset 1961–2017; Østby et al. 2017). The trend line (A-C, E) displays the rate of change (±2SE) if the indicator value is assumed to be constant (solid grey and dashed) in the climatic reference period and NOT assumed to be constant (dotted; A-C and E) in the climatic reference period, but equal to the predicted regression line for the period 1961–1990.

2.2. Primary productivity

Primary productivity can be quantified as e.g. phenology or maximum productivity during the summer season. The recent assessment of ecosystem condition in the Norwegian Arctic tundra found a trend towards an earlier start of the growing season and increased maximum productivity, measured with satellite imagery between 2000-2019 (Pedersen et al. 2021c). There is, however, considerable spatial heterogeneity in the observed patterns. Accordingly, current changes in primary productivity still have limited impact on the ecological condition of the tundra ecosystem.

A recent pan-Arctic study found that reproductive phenology responds stronger to experimental warming than vegetative phenology (Collins et al. 2021). Flowering, end of flowering and seed dispersal all advanced with a moderate experimental warming, and the vegetation greened earlier and senesced later, resulting in a prolonged growing season. The average advances in leaf green-up and reproductive phenology were 0.7–2.9 days and delay in leaf senescence 0.8 days. These results highlight the importance of combining satellite-based data, typically only available at coarse temporal and spatial resolution, with detailed field studies to better understand drivers of the observed heterogeneity and to enhance the interpretation of changes in primary productivity in a food web context. This is critical, as herbivore populations are expected to be impacted by an altered timing of the phenological states (e.g. Lameris et al. 2019).

New satellite data, such as the Sentinel-2 mission, are expected to resolve the challenges of spatial and temporal resolution. Cloud coverage, however, remains an issue even with the frequent passages of the Sentinel satellites over Svalbard. Moreover, the linkage between ground observations and Sentinel-2 based estimates of growing season start are not uniform across the tundra habitats (Karlsen et al. 2021). There is a need to investigate several aspects of the different satellite time series to improve data quality and enhance comparison between the current MODIS time series and the emerging Sentinel-2 data. Field-based validation is required to understand what implications the satellite-observed changes have for nutrient content, compositional change and phenology of the tundra vegetation. To improve our understanding of changes in primary productivity and its implications for the food web, the COAT Svalbard vegetation work makes use of herbivore exclosures, monitoring at 57 field stations, imagery acquired with drones and satellites, and analysis of plant and soil nutrient contents (Ravolainen et al. 2020).

2.3. Changes in higher trophic levels and overall trends in monitoring targets

The Svalbard tundra ecosystem has undergone rapid and substantial changes in abiotic conditions, particularly increasing temperatures, longer and warmer growing seasons, shorter snow-cover seasons, and thawing of permafrost. The biotic implications of these changes are still mostly limited, and mainly evident in ecosystem characteristics (e.g., landscape-ecological patterns and biological diversity) and indicators (e.g., Arctic endemic species and plant communities) with strong causal links to climate (Appendix 4).

Currently, the abundance of monitored vertebrate populations appears to be stable or increasing (reindeer, ptarmigan, fox and geese; Fauteux et al. 2021; Hansen et al. 2019b; Johnson et al. 2020; Layton-Matthews et al. 2020; Marolla et al. 2021; Nater et al. 2021) (Figure 3). There could be several reasons for this. The monitored herbivores include resident and migratory species that are at the northern edge of their distribution range. They are adapted to harsh conditions, including food limitations and extreme cold, but show considerable plasticity. Thus, longer growing seasons would reduce food constraints and allow for better body condition, leading to increased reproduction (Albon et al. 2017; Loe et al. 2021). While stochastic perturbations in the form of large-scale rain-on-snow (ROS) events and resultant basal ice continue to affect annual variability in population growth rates of many species, their impacts may be at least partially alleviated by

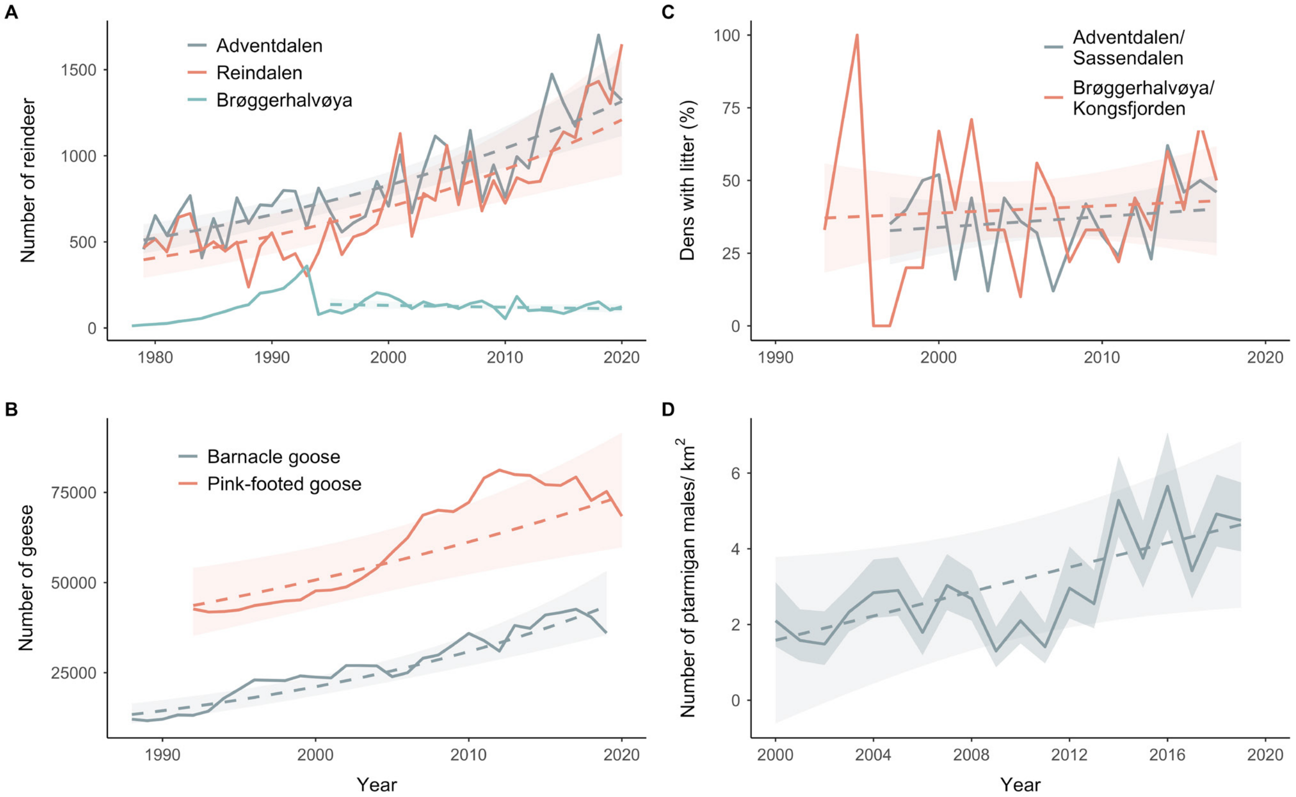

Figure 3: Time-series of the abundances of four key vertebrate species. A) Population size of Svalbard reindeer (modified from Pedersen et al. 2021c). B. Population size of Svalbard pink-footed goose and barnacle goose (modified from Pedersen et al. 2021c). C. Arctic fox dens with pups (modified from Layton-Matthews et al. 2020; Pedersen et al. 2021c). D) Number of ptarmigan males per square kilometer (modified from Marolla et al. 2021).

improved summer conditions. Indeed, while severe winter weather events can have drastic short-term consequences, Hansen et al. (2019a) documented that they may have a stabilising effect on reindeer population dynamics in the long run. Tundra plants respond immediately to warming summer temperatures by increasing growth (Van der Wal and Stien 2014), and both reindeer and geese can have local effects on plant biomass and modify the tundra vegetation communities (Ravolainen et al. 2020). Consequently, changes in their abundance, interacting with climate warming, are expected to have 'knock-on effects' on the composition, structure and productivity of the Svalbard vegetation communities.

The observed shift in bioclimatic zonation towards a low-Arctic zone provides suitable growing conditions for a higher diversity of plants and the potential for establishment of new functional groups (e.g., shrubs). Such changes in plant communities are not yet apparent. This may be due to long time-lags in vegetation community-level responses to climate. However, there is presently a lack of long-term monitoring data suitable for documenting slow community-level vegetation transitions (Ravolainen et al. 2020). This represents a major gap in our capacity to assess climate change impacts on tundra vegetation, including the cascading effects on food web dynamics and overall ecosystem functioning. COAT aims to fill this gap by establishing the required long-term monitoring and model-based analyses for disentangling changes in key food web processes (e.g., Ims and Yoccoz 2017; Ravolainen et al. 2020). This will provide a solid foundation for a better understanding of climate change impacts on the ecological condition of high-Arctic tundra ecosystems.

3. Unanswered questions, challenges and recommendations for the future

Long-term ecosystem-based monitoring is crucial to (1) establish how anthropogenic pressures affect the ecosystem, and to (2) assess the effectiveness of management actions (Christensen et al. 2020; Ims and Yoccoz 2017). Key success criteria are co-location of measurements at ecologically relevant spatial and temporal scales, harmonised and standardised methods, and procedures for data integration from observations and experiments to models of causal relations (Ims and Yoccoz 2017; Musche et al. 2019). For the long-term running of the ecosystem-based monitoring, we recommend the following:

Climatic drivers of ecosystem change: The ecosystem implications of a rapidly warming climate are central and a generally important arena for interdisciplinary research. COAT Svalbard scientists have quantified climate effects on central state variables in the monitoring modules (summarised in Pedersen et al. 2021a, Table 4). For example, ptarmigan population dynamics are mainly affected by increased winter temperature (Appendix 5; Marolla et al. 2021), while reindeer body mass and subsequent reproduction are driven by ROS events and the onset of snow in autumn (Loe et al. 2021). Further identification of such driver–response relationships ought to be given high priority.

COAT Svalbard has established observational time series of snow properties. However, the understanding of ecosystem impacts of changing snow conditions requires snow modelling products that provide accurate, spatially distributed and time-evolving datasets of snow properties. This can be acquired through the data-model fusion system that merges available observational datasets on snow properties with state-of-the-art, high-resolution (1- to 500-metre scale), physically based snow models.

New methods and technologies: Ecosystem monitoring has entered an era where new technologies allow for automatic measurements that are spatially and temporally more extensive and have higher resolution than traditional manual measurements. Such ground (automatic sensors) and remotely (drones, satellites) based technologies should be optimised to improve the scope of field measurements (see examples in Kleiven et al. 2021; Mölle et al. 2021). There is a substantial effort involved in consolidating sensor-based data to ecosystem processes occurring on the ground. New developments should also include analytical tools (algorithms) to improve 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 such state variables.

Interface with end-users and cooperation: It is COAT's ambition to be highly relevant to policy makers and managers. Given the prospects of climate change, Arctic ecosystems are likely to be transformed beyond scientists' current abilities to make predictions and managers' capacity to implement mitigation and adaptation strategies. This grand challenge requires more sincere efforts to develop structured interfaces between monitoring-based ecosystem science and end-users than are presently implemented within COAT Svalbard (Ims and Yoccoz 2017; see Pedersen et al. 2021a, Table 4, for an overview and Henden et al. 2020 for an example).

4. Data availability

The COAT data management system is a crucial part of the research infrastructure. COAT's data portal (https://data.coat.no/) builds on international metadata standards (DCAT, schema.org-structured data and ISO 19115/CSW) compatible with SIOS's digital infrastructure. See Appendix 6 for a list of dataset sources in this chapter and Pedersen et al. (2021c; Table 3.2.b) for a complete list of all dataset sources for the indicators/state variables summarised in section 2.

5. Acknowledgements

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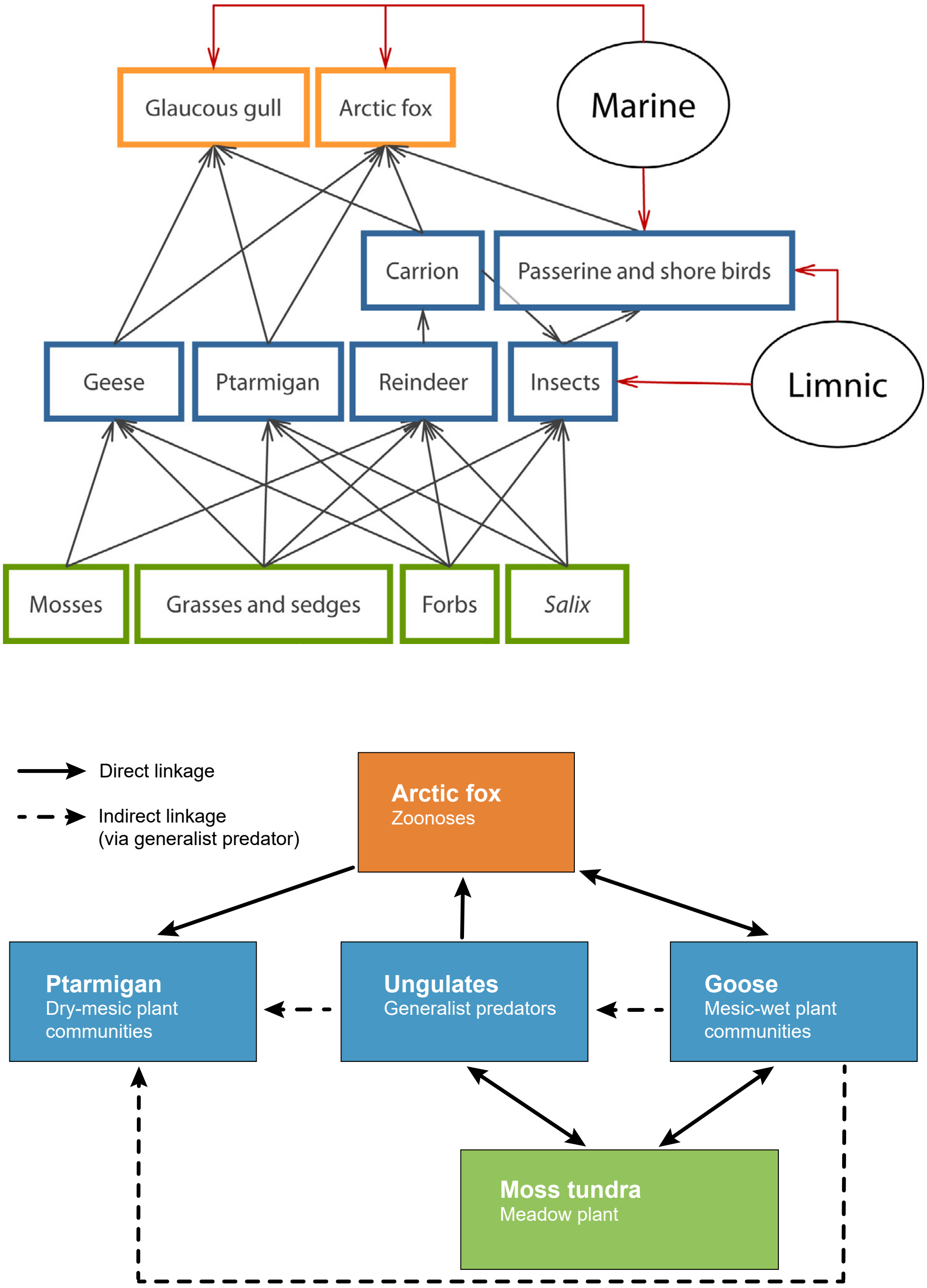
Appendix 1: The Svalbard terrestrial food web and the COAT monitoring modules



The terrestrial food web in Svalbard (upper panel) is represented with (lower panel) five biotic and one cross-cutting climate monitoring module (not shown here). For a detailed description of the Svalbard terrestrial tundra ecosystem, see Box 1 in Pedersen et al. (2020)[1] and Descamps et al. (2017)[2].

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[1] Pedersen ÅØ, Jepsen JU, Paulsen IMG et al (2021c) Norwegian Arctic tundra: a panel-based assessment of ecosystem condition. Report Series 153. Norwegian Polar Institute, Tromsø

[2] Descamps S, Aars J, Fuglei E, et al (2017) Climate change impacts on wildlife in a High Arctic archipelago - Svalbard, Norway. Glob Change Biol 23:490-502. https://doi.org/10.1111/gcb.13381

Appendix 2: COAT Climate monitoring network

The climate module covers the main climatic variables that are expected to act as drivers on ecosystem components, i.e. air and soil temperature, precipitation, wind direction and speed, snow cover and depth, air humidity, radiation, basal ice cover, and timing of snowmelt.

Full-scale operational weather stations are a core infrastructure in COAT's climate monitoring network. They cover an important ecological gradient from the coast to inland valleys. Along with the weather stations, a network of ground temperature loggers was established to measure both temperature and soil moisture along elevational gradients, at module stations and in a network around selected weather stations.

The data from the COAT stations are also essential to calibrate spatial and temporal snow models (see Liston and Elder 2006[3] for an example), as the cryosphere has a key role in determining the dynamics of the Svalbard tundra ecosystem (e.g. Hansen et al. 2013[4]; Stien et al. 2012[5]).

The weather stations are 'hot-spots' for potential co-location and expansion of measurements to cover a wider range of variables related to both the biosphere and the cryosphere. Data from the weather stations can be downloaded from www.seklima.met.no/observations/.

Photos: Ketil Isaksen

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[3] Liston GE, Elder K (2006) A meterological distribution system for high resolution terrestrial modelling (MicroMet). J. Hydrometeor 7: 217-234. https://doi.org/10.1175/JHM486.1

[4] Hansen BB, Grøtan V, Aanes R et al (2013) Climate events synchronize the dynamics of a resident vertebrate community in the High Arctic. Science 339:313-315. https://doi.org/10.1126/science.1226766

[5] Stien A, Ims RA, Albon SD et al (2012) Congruent responses to weather variability in high Arctic herbivores. Biol Lett 8:1002-1005. https://doi.org/10.1098/rsbl.2012.0764

Appendix 3: Biotic and abiotic indicators for each of the seven ecosystem characteristics addressed in the assessment of Arctic tundra in Svalbard

The reference condition, relative to which all assessments of current ecosystem condition should be made, is defined as 'an intact ecosystem state', which is characterised by the maintenance of the fundamental ecosystem structures, functions and productivity. The majority of indicators were derived from COAT, with support from SIOS, and the Environmental Monitoring of Jan Mayen and Svalbard (MOSJ) programme, dedicated specifically to the monitoring of Norwegian Arctic tundra ecosystems. See section 5 and Tables in Pedersen et al. (2021c)[6] for associated information.

Ecosystem characteristic	Indicator
Primary productivity	Maximum vegetation productivity
	Start of growing season
Biomass between trophic levels	Maximum vegetation productivity versus Svalbard reindeer
	Maximum vegetation productivity versus geese
	Herbivorous vertebrates versus Arctic fox
Functional groups within trophic levels	Herbivorous vertebrates
Functionally important species and biophysical structures	Pink-footed goose abundance
	Barnacle goose abundance
	Svalbard reindeer abundance
	Svalbard reindeer mortality rate
	Svalbard reindeer calf rate
	Arctic fox abundance
Landscape-ecological patterns	Bioclimatic subzones
	Wilderness areas
Biological diversity	Svalbard rock ptarmigan breeding abundance
Abiotic factors	Days with extreme cold
	Winter melt days
	Degree days
	Growing degree days
	Annual mean temperature
	July mean temperature
	Annual precipitation
	Permafrost
	Snow cover duration

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6 Pedersen ÅØ, Jepsen JU, Paulsen IMG et al (2021c) Norwegian Arctic tundra: a panel-based assessment of ecosystem condition. Report Series 153. Norwegian Polar Institute, Tromsø

Appendix 4: Key conclusions from the assessment of ecological condition of Norwegian Arctic tundra

- Norwegian Arctic tundra ecosystems have since the climatic reference period (1961–1990) undergone rapid and substantial changes in the abiotic conditions manifested particularly as increasing surface temperatures, longer and warmer growing seasons, shortening of the snow-covered season, and increasing permafrost temperatures.

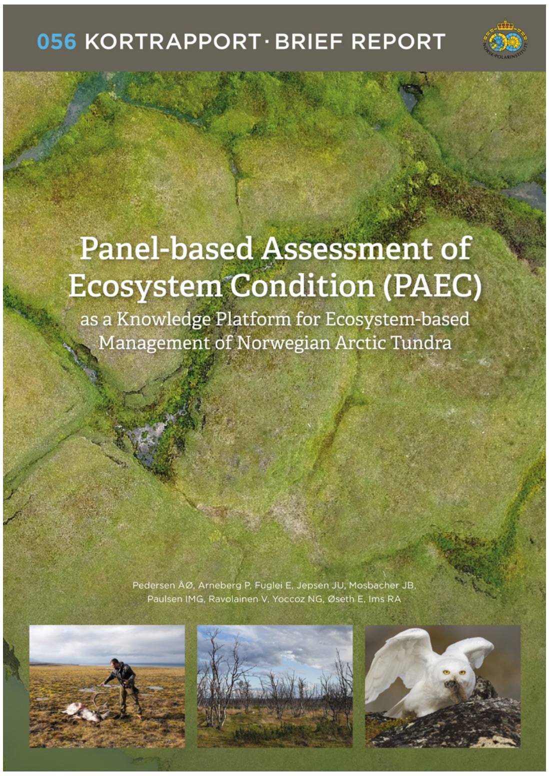
- The biotic implications of these changes are still mostly limited, and mainly evident in ecosystem characteristics (Landscape-ecological patterns and biological diversity) and indicators (e.g. Bioclimatic subzones, Arctic and endemic species, Plant communities) with strong causal links to climate.

- The scientific panel concludes that Norwegian Arctic tundra ecosystems are overall in a good ecological condition, with fundamental structures and functions still maintained, despite substantial abiotic changes. However, some biotic ecosystem characteristics show deviations from the reference condition, while others are presently on significant change trajectories, which should be considered a warning of more extensive, incipient ecosystem changes. Of the two sub-ecosystems assessed, the low-Arctic tundra in Finnmark shows more pronounced and consistent deviations in biotic characteristics than the high-Arctic tundra in Svalbard. In Finnmark, the Arctic tundra ecosystems are on a trajectory of losing Arctic endemic species (Arctic fox and snowy owl) and are bioclimatically on a trajectory away from low-Arctic subzones towards boreal subzones.

Reports can be downloaded at:

https://brage.npolar.no/npolar-xmlui/handle/11250/2754696

https://brage.npolar.no/npolar-xmlui/handle/11250/2754717

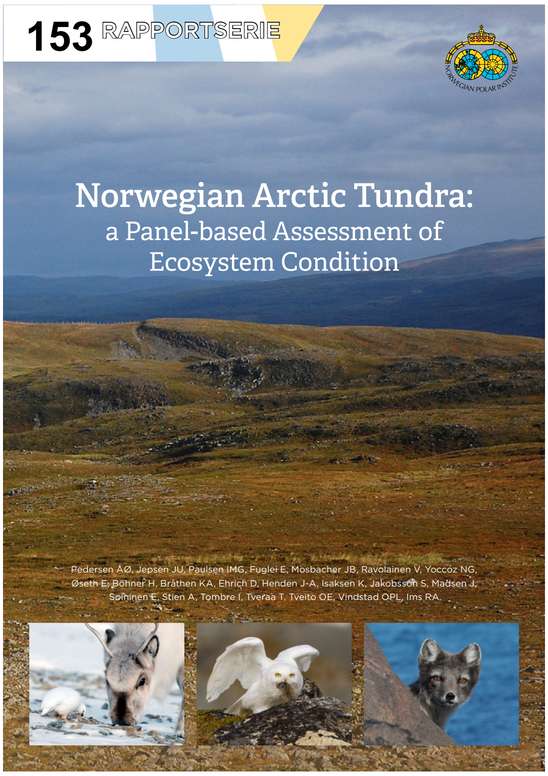


056 KORTRAPPORT · BRIEF REPORT

Panel-based Assessment of Ecosystem Condition (PAEC)

as a Knowledge Platform for Ecosystem-based Management of Norwegian Arctic Tundra

Pedersen ÅØ, Arneberg P, Fuglei E, Jepsen JU, Mosbacher JB, Paulsen IMG, Ravolainen V, Yoccoz NG, Øseth E, Ims RA



153 RAPPORTSERIE

Norwegian Arctic Tundra:

a Panel-based Assessment of Ecosystem Condition

Pedersen ÅØ, Jepsen JU, Paulsen IMG, Fuglei E, Mosbacher JB, Ravolainen V, Yoccoz NG, Øseth E, Böhner H, Bråthen KA, Ehrich D, Henden J-A, Isaksen K, Jakobsson S, Madsen J, Soininen E, Stien A, Tombre I, Tveraa T, Tveito OE, Vindstad OPL, Ims RA.

Appendix 5: Iterative model predictions for wildlife populations impacted by rapid climate change

Marolla et al. (2021)[7] used MOSJ and COAT long-term monitoring data of Svalbard rock ptarmigan and other biotic and abiotic ecosystem state variables to identify drivers of population dynamics and to evaluate the ability of state-space models to predict next-year ptarmigan density. Firstly, they laid out the hypothesised impacts of the biotic and abiotic drivers on ptarmigan dynamics and visualised them through the conceptual COAT model. They then fitted state-space models to Svalbard rock ptarmigan monitoring data to 1) quantify the effects of potential drivers of population dynamics (explanatory predictions) and 2) assess the ability of candidate models of increasing complexity to forecast next-year population density (anticipatory predictions).

Benefitting from the ecosystem-wide monitoring data, they were able to attribute a recent increasing trend in the ptarmigan population to major changes in winter climate, especially in terms of mean temperature. As winters become warmer, ptarmigan appear to benefit from these conditions, likely because their energy needs for thermoregulation are reduced. This probably improves their body condition throughout the winter and thus increases survival. The strong positive effect of increasing winter temperature on ptarmigan population growth currently outweighs the negative impacts of other manifestations of climate change, e.g., rain-on-snow events. The ptarmigan population also appears to compensate for the impact of the main manageable driver, i.e., current harvest levels.

This study highlights the value of the ecosystem-wide COAT monitoring in Svalbard and the application of multi-driver statistical modelling based on these monitoring data to assess and forecast the state of Svalbard rock ptarmigan populations.

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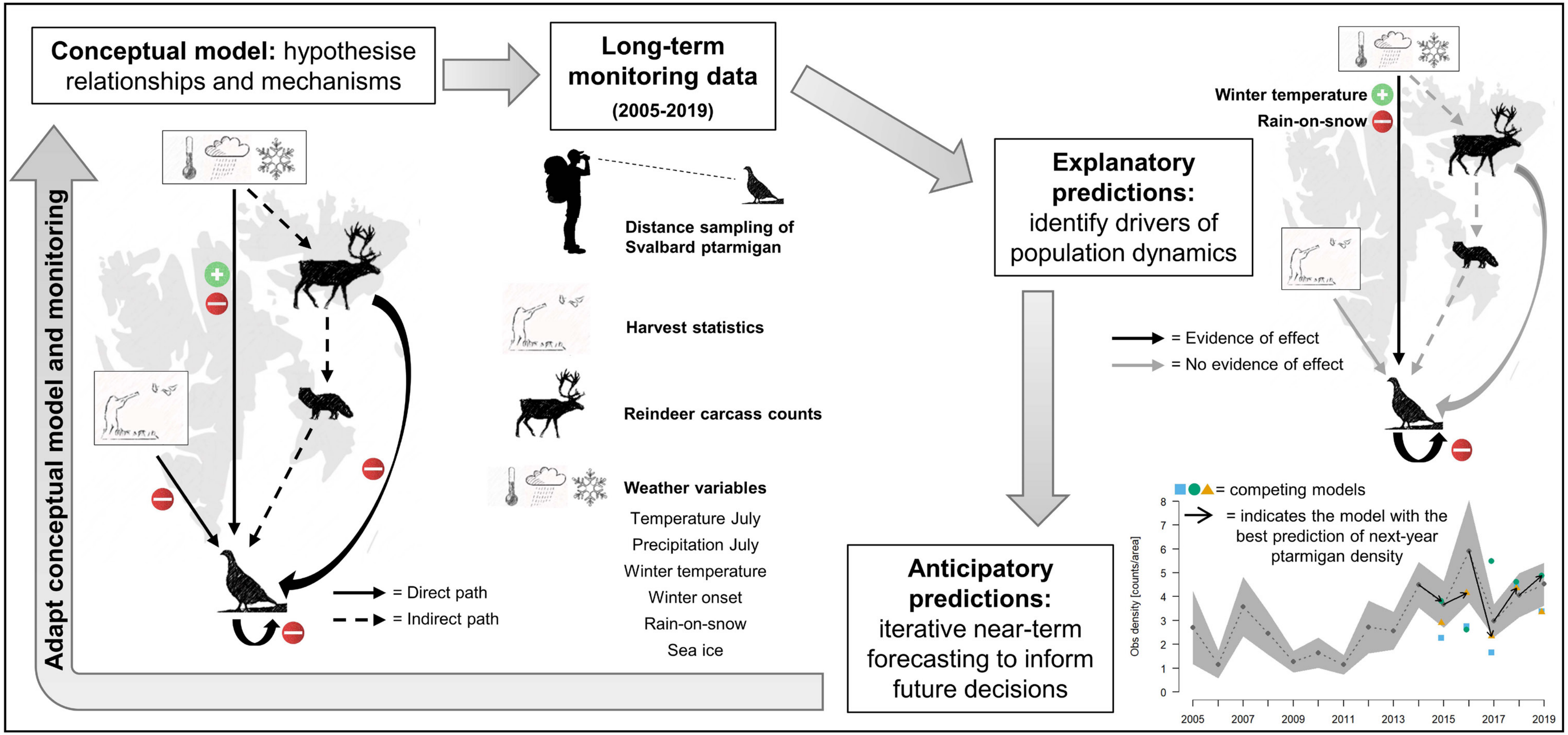
[7] Marolla F, Henden JA, Fuglei E, Pedersen ÅØ, Itkin M, Ims RA (2021) Iterative model predictions for wildlife populations impacted by rapid climate change. *Global Change Biology*, *27*(8), 1547-1559. https://doi.org/10.1111/gcb.15518



Graphical abstract, modified from Marolla et al. (2021) and Pedersen et al. (2021a)[8], describing the approach used to model the effects of manageable and non-manageable drivers on population dynamics of Svalbard rock ptarmigan.

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[8] Pedersen ÅØ, Arneberg P, Fuglei E et al (2021) Panel-based Assessment of Ecosystem Condition as a platform for ecosystem-based management of Norwegian Arctic tundra. Brief Report 056, Norwegian Polar Institute

Appendix 6: Summary of datasets and their availability

Overview of dataset name, owner institutions, temporal coverage and DOI/URL. The table is modified from Pedersen et al. (2021c; Table 3.2.b[9]).

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
Arctic fox den monitoring (data are partly excluded from the public)	Number of active dens	1993/97–2019	Adventdalen and Sassendalen, Svalbard	http://www.mosj.no/en/fauna/terrestrial/arctic-fox-population.html	Eva Fuglei, NPI (eva.fuglei@npolar.no)
Svalbard Barnacle goose wintering population census	Population counts Demography	1988–2020	Svalbard archipelago (winter counts in Scotland and England)	https://monitoring.wwt.org.uk/our-work/goose-swan-monitoring-programme/species-accounts/svalbard-barnacle-goose/	Wildfowl & Wetlands Trust (WWT)
Svalbard Pink-footed goose spring population census	Population counts Demography	1991-2018	Svalbard archipelago (winter counts in Denmark, Belgium and the Netherlands)	https://www.sciencebase.gov/catalog/item/5cc8890ee4b09b8c0b77f1cd	Jesper Madsen, AU (jm@bios.au.dk)
MODIS EVI	Vegetation productivity	2000–2019	Svalbard archipelago	e4ftl01.cr.usgs.gov/MOLT/MOD13Q1.006/	NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. Moderate-resolution Imaging Spectroradiometer (MODIS) Terra
Svalbard reindeer population abundance and calf rates	Population counts Demography	1978/79–2020	Adventdalen, Brøggerhalvøya, Reindalen	http://www.mosj.no/en/fauna/terrestrial/svalbard-reindeer-population.html https://data.coat.no/dataset/s_ungulates_abundance_kongsfjorden_summer_v1 https://data.coat.no/dataset/s_ungulates_summary_adventdalen_summer_v1	Åshild Ø. Pedersen, NPI (ashild.pedersen@npolar.no) Audun Stien, NINA (audun.stien@uit.no)
Svalbard reindeer carcass abundance	Number of carcasses	1979/1991–2020	Adventdalen	https://data.coat.no/dataset/s_ungulates_carcasses_adventdalen_summer_v3	Åshild Ø. Pedersen, NPI

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[9] Pedersen ÅØ, Jepsen JU, Paulsen IMG et al (2021) Norwegian Arctic Tundra: a Panel-based Assessment of Ecosystem Condition. Report Series 153. Norwegian Polar Institute, Tromsø

Svalbard rock ptarmigan breeding abundance	Population counts	2000–2019	Nordenskiöld Land	https://data.coat.no/dataset/s_ptarmigan_counts_v3	Eva Fuglei, Åshild Ø. Pedersen, NPI
Sval-Imp gridded temperature	Temperature (degrees)	1958–2017	Svalbard archipelago	https://doi.org/10.11582/2018.00006	Ole Einar Tveito, MET Norway (oleet@met.no)
Sval-Imp gridded precipitation	Precipitation (in mm)	1958–2017	Svalbard archipelago	https://doi.org/10.11582/2018.00006	Ole Einar Tveito, MET Norway
Sval-Imp gridded snow cover	Fractional snow cover	1958–2017	Svalbard archipelago	https://doi.org/10.11582/2018.00006	Ole Einar Tveito, MET Norway
Solid precipitation	Fraction of solid precipitation	1969-2020	Longyearbyen, Ny-Ålesund	https://doi.org/10.1175/JHM-D-19-0252.1	Eirik Førland, MET Norway (eirikf@met.no)
Permafrost monitoring	Permafrost temperature Depth of active layer	1999–2020	Adventdalen	www.mosj.no/en/climate/land/permafrost.html	Ketil Isaksen, MET Norway (ketili@met.no)
COAT weather stations	Precipitation, temperature, wind speed	2020-	Nordenskiöld Land, Brøggerhalvøya, Kaffiøyra	https://seklima.met.no/observations/	Ketil Isaksen, MET Norway