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Norwegian Arctic Tundra:
a Panel-based Assessment of Ecosystem Condition

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Norwegian Arctic Tundra: a Panel-based Assessment of Ecosystem Condition

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Preface

On behalf of the Ministry of Climate and Environment, the Norwegian Environment Agency is responsible for the development of the *System for assessment of ecological condition* of terrestrial and marine ecosystems. This report is the product of a project funded by the Norwegian Environment Agency and includes the first assessment of the ecological condition of Norwegian Arctic tundra in two sub-ecosystems — High Arctic tundra in Svalbard and Low Arctic tundra on the Norwegian mainland.

The *Panel-based Assessment of Ecosystem Condition* (PAEC) is one of two methods developed for use in the *System for assessment of ecological condition*. PAEC forms the basis for a consolidated, evidence-based assessment of the ecological condition of an ecosystem. In 2019, scientists involved in this assessment described the development and tested a pilot version of the PAEC protocol for Arctic tundra and the Arctic part of the Barents Sea (Jepsen et al. 2019). Based on lessons learned from these two ecosystems, the PAEC protocol has been improved and translated into English (Jepsen et al. 2020). The Norwegian Environment Agency commissioned in 2020 the Norwegian Polar Institute to lead the work with the first operational PAEC of Norwegian Arctic tundra together with other institutions involved in the *Climate-ecological Observatory for Arctic Tundra* (COAT), which we report on here.

The PAEC of Arctic tundra involved five central institutions in COAT — Norwegian Polar Institute (NPI), Norwegian Institute for Nature Research (NINA), Norwegian Meteorological Institute (MET), UiT The Arctic University of Norway (UiT), and Aarhus University (AU). The work was conducted by a panel consisting of 21 participants under the leadership of Åshild Ønvik Pedersen (NPI), in close cooperation with Jane U. Jepsen (NINA), Rolf Anker Ims and Nigel Yoccoz (UiT), Eva Fuglei (NPI), Jesper Mosbacher (NPI), and Virve Ravolainen (NPI). Ellen Øseth (NPI) had an administrative role in the scientific panel and acted as a secretary during the assessment phase, while Ingrid M. Paulsen (NPI) was engaged full-time to participate and assist in the process.

The work was conducted from 1st June 2020 to 26th March 2021. The PAEC process consists of four phases: 1) The scoping phase where new and existing indicators are evaluated for inclusion; 2) the analysis phase where indicator analyses are updated from the pilot assessment (Jepsen et al. 2019) and new indicators are developed; 3) the assessment phase where the scientific panel meets and discusses the significance and validity of indicator analyses, and; 4) the report phase where the scientific background material and conclusions from the scientific panel is written up in a report according to the PAEC protocol.

Covid-19 restrictions influenced the entire project period, and due to these restrictions, there were no physical meetings involving the entire panel. Instead, a number of, mostly digital, meetings involving smaller sections of the panel were held. The entire panel met digitally for the formal assessment meeting (Phase 3) over two days 16th–17th November 2020.

We thank the Norwegian Environment Agency for valuable contributions to the process and quality assurance of the report. Else Marie Løbersli and Eirin Bjørkvoll were contacts for the project. We further thank Gunn Sissel Jaklin (NPI) for proof-reading the report, Ivar Stokkeland (NPI) for assistance with the reference lists, Leif Einar Støvern (UiT) for assistance with photos and Stein Tore Pedersen (NPI) for assisting the project leader.

Tromsø/Longyearbyen 26th March 2021

Åshild Ønvik Pedersen
Project leader

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Summary

The *System for Assessment of Ecological Condition*, coordinated by the Norwegian Environment Agency, is intended to form the foundation for evidence-based assessments of the ecological condition of Norwegian terrestrial and marine ecosystems not covered by the EU Water Framework Directive. This report describes the first operational assessment of the ecological condition of Norwegian Arctic tundra ecosystems — High Arctic tundra in Svalbard and Low Arctic tundra in Finnmark. The assessment method employed is the *Panel-based Assessment of Ecosystem Condition* (PAEC; Jepsen et al. 2020).

Central premises of the assessment

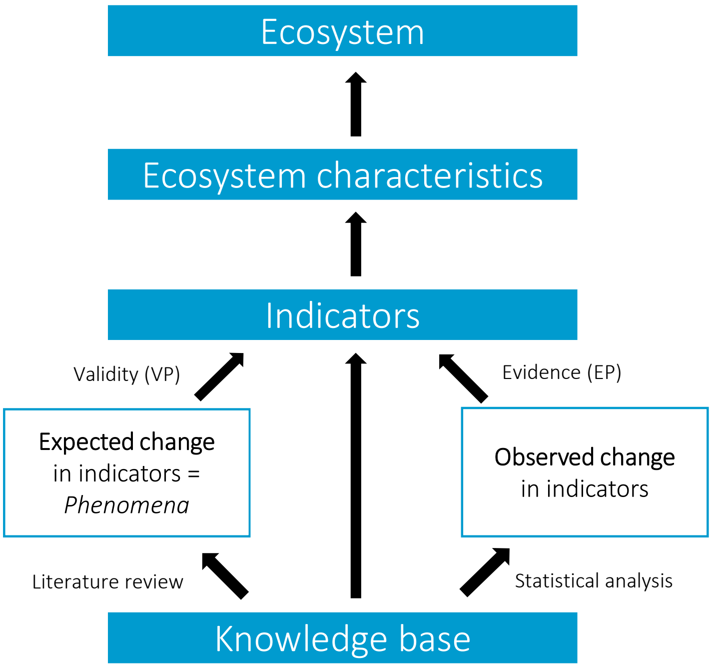
The current assessment of Arctic tundra adheres to the premises of the *System for Assessment of Ecological Condition* outlined in Nybø & Evju (2017). This work recommends that each ecosystem assessment addresses seven specific ecosystem characteristics, each represented by a set of biotic and/or abiotic indicators. 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. This implies that the structural and functional characteristics of the ecosystem is under limited influence from human pressures. The report further defines a reference climate as "*a climate as described for the climatic normal period 1961–1990*" (see Ch. 2 for full definitions from Nybø & Evju 2017).

Key conclusions from the assessment of 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*, *Plant communities*, and indicators related to Arctic and endemic species) with strong causal links to climate.
- The scientific panel concludes that Norwegian Arctic tundra ecosystems are overall in a <u>good ecological condition</u>, 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 is bioclimatically on a trajectory away from Low Arctic subzones towards boreal subzones.

Fundamental principles in PAEC

PAEC is a structured protocol for assessing the condition of an ecosystem relative to a reference condition. The protocol is hierarchical and gradually builds up from an assessment of the available knowledge base, through formulation of expected changes in indicators (phenomena), evaluation of observed changes in each indicator by means of statistical analysis (estimation of change rates), to integrated assessments of the condition of each ecosystem characteristic and the ecosystem as a whole (see figure below).



A schematic summary of the hierarchy in a PAEC assessment. The four main levels in PAEC (blue boxes) are assessments of 1) the knowledge base, 2) the condition of individual indicators, 3) the condition of ecosystem characteristics, and 4) the condition of the ecosystem as a whole. The assessment of the individual indicators rests upon the extent to which expected changes in indicators (phenomena) are supported by evidence of observed changes based on statistical analysis (estimation of change rates) of the underlying data.

The formulation of phenomena is central in PAEC. The phenomena specify causal links between anthropogenic drivers of change and indicators of ecosystem function and structure, based on peer review literature (see examples below). The causal links are verbally expressed in terms of qualitative predictions (hypotheses) on directions of change trajectories for ecological indicators and their ecosystem significance. The scientific certainty of the predictions is assessed in terms of the *Validity of the phenomenon* (VP) based on prior scientific knowledge (i.e. peer reviewed literature), while the data analyses of PAEC conclude to what extent observed trajectories (i.e. estimated rates of change) are consistent with the prediction (EP — *Evidence for phenomenon*).

Central to PAEC is also an explicit focus on the different sources of uncertainty implied by the available datasets, which impinge on the assessments. Only one of these sources can be assessed in quantitative terms; i.e. the confidence intervals of the estimated rate of change of the individual indicators obtained from the statistical time series analysis of monitoring data. Spatial and temporal components of the data coverage of indicators, as well as the indicator coverage of the seven ecosystems characteristics, must be assessed qualitatively, however, based on a stringent set of criteria defined by the technical description of PAEC (Jepsen et al. 2020).

All assessments are done by a scientific panel in PAEC. The panel for Arctic tundra consisted of 20 experts with a pertinent expertise on the focal ecosystem characteristics and analytical methods to assess them. The PAEC protocol (Jepsen et al. 2020) details how each phase in the assessment should be performed and documented, from initial scoping, through data analysis, to the overall assessment and reporting, including specifically defined assessment categories or rules for the main levels in the assessment.

Examples of indicators/phenomena for Low Arctic tundra and High Arctic tundra.

Low Arctic tundra

Indicator: Ptarmigan density

Phenomenon: Low or decreasing populations of willow ptarmigan

Explanation: Climate change affect ptarmigan density negatively through seasonal changes and increased precipitation during critical periods. Dampened rodent cycles, altered predation pressure and harvesting also impact the populations.

High Arctic tundra

Indicator: Svalbard reindeer mortality

Phenomenon: High or increasing mortality of Svalbard reindeer

Explanation: Svalbard reindeer mortality is tightly linked to density dependence and winter weather. Mortality increases in winters with prevalent ground ice, which limits food access for the reindeer, in combination with high reindeer densities.

Photos: G. Vie/UiT (upper left), E. Fuglei/NPI (upper right), M.A. Strømseng/UiT (lower left), J. Kohler/NPI (lower right)

Datasets and indicators used in the assessment

The assessment of the condition of Arctic tundra ecosystems is based on analyses of 34 datasets (Ch. 3) supporting 16 indicators shared between the two focal sub-ecosystems, 26 indicators unique to Low Arctic tundra and eight indicators unique to High Arctic tundra ecosystems (Ch. 4). The majority of indicators are derived from the ecosystem-based *Climate-ecological Observatory of Arctic Tundra* (COAT) and *Environmental Monitoring of Jan Mayen and Svalbard* (MOSJ), dedicated specifically to the monitoring of Norwegian Arctic tundra ecosystems. In addition, gridded climatic data were derived from the Norwegian Meteorological Institute's national services. The total set of indicators encompasses all seven ecosystem characteristics for the two sub-ecosystems. The indicator coverage (assessed to three categories) varies from "Inadequate" to "Adequate" for the different characteristics and is better for Low Arctic tundra than for High Arctic tundra.

Most of the biotic datasets cover a time period of 15–30 years, while the climatic data cover 60 years; the climatic reference period (1961–1990; defined in *System for Assessment of Ecological Condition,* Ch. 2) and the following 30-year period (1991–present). The data coverage (assessed to four categories depending on spatial and temporal representativity; Table 7.1a, b) is better for the Low Arctic (90 % of indicators in the top two categories "Very good" and "Good") than for the High Arctic (67 % of indicators in the top two categories).

The condition of ecosystem characteristics

The seven ecosystem characteristics considered in the *System for Assessment of Ecological Condition* are: *Primary productivity*, *Biomass distribution among trophic levels*, *Functional groups within trophic levels, Functionally important species and biophysical structures*, *Landscape-ecological patterns, Biological diversity,* and *Abiotic factors* (see Ch. 2 for a normative description of the reference condition for each ecosystem characteristic). The overall condition of each ecosystem characteristic is assessed as belonging to one of three categories with increasing deviation from the reference condition — from no to substantial deviation (see definitions below). The choice of category is primarily dependent on the validity of (VP) and the evidence for (EP) each phenomenon associated with a given characteristic. A phenomenon is a description of expectations, so-called scientific hypotheses, for how each indicator changes towards a worse state as a result of anthropogenic ecosystem drivers. Ecosystem characteristics that are assessed as belonging to ***limited deviations*** from the reference condition show changes that indicate they are on a trajectory away from an intact ecosystem. Ecosystem characteristics that are assessed as belonging to ***substantial deviation*** from the reference condition can no longer be considered representative of an intact ecosystem.

Shortened definitions of the three assessment categories. For full definitions see chapter 7.3 and Jepsen et al. (2020).

No deviation from the reference condition
An ecosystem characteristic assigned to this category can be considered in good ecological condition based on the current set of indicators. The ecosystem characteristic shows no or limited deviations from the reference condition.

Limited deviation from the reference condition
An ecosystem characteristic assigned to this category can be considered in good ecological condition based on the current set of indicators. However, the ecosystem characteristic shows changes in a direction of worsened ecological condition, which requires attention.

Substantial deviation from the reference condition
An ecosystem characteristic assigned to this category can NOT be considered in good ecological condition based on the current set of indicators. The ecosystem characteristic shows substantial deviations from the reference condition.

Based on scientific validity and evidence for underlying phenomena related to the indicators, the conclusions of the expert panel for each ecosystem characteristic are summarised below for both sub-ecosystems.

For **Low Arctic tundra in Finnmark** all ecosystem characteristics deviate from the reference condition, either to a limited or substantial degree. Four characteristics (*Primary productivity*, *Biomass distribution among trophic levels, Functional groups within trophic levels* and *Functionally important species and biophysical structures)* show ***limited deviation*** from the reference condition, while three characteristics (*Landscape-ecological patterns*, *Biological diversity* and *Abiotic factors*) show ***substantial deviation*** from the reference condition.

For **High Arctic tundra in Svalbard**, two ecosystem characteristics (*Functional groups within trophic levels* and *Biological diversity*) show ***no deviation*** from the reference condition, but both have an "inadequate" indicator coverage, meaning that the set of indicators has severe shortcomings in terms of representing these ecosystem characteristics. Of the remaining characteristics, three (*Primary productivity*, *Biomass distribution among trophic levels* and *Functionally important species and biophysical structures)* show ***limited deviation***, while two (*Landscape-ecological patterns* and *Abiotic factors)* show ***substantial deviation*** from the reference condition.

Summary of the condition assessments for each of the seven ecosystem characteristics of Low and High Arctic tundra

	Low Arctic tundra — Finnmark	High Arctic tundra — Svalbard
Primary productivity	Based on the set of indicators this ecosystem characteristic is assessed as having ***limited deviation from the reference condition***. The assessment is based on 3 indicators with 3 associated phenomena. There is evidence of changes towards a worsened condition consistent with phenomena attributed to climate change, but the magnitudes of these changes are so small and/or heterogeneous that they are assessed to have overall limited impact on ecological condition.	Based on the set of indicators the ecosystem characteristic is assessed as having ***limited deviation from the reference condition***. The assessment is based on 2 indicators with 2 associated phenomena with high validity and good data coverage. There is evidence of changes towards a worsened condition consistent with phenomena attributed to climate change, but the magnitudes of these changes are so small and/or heterogeneous that they are assessed to have overall limited impact on ecological condition.
Biomass distribution among trophic levels	Based on the set of indicators this ecosystem characteristic is assessed as having ***limited deviation from the reference condition***. The assessment is based on 4 indicators with 4 associated phenomena with intermediate to high validity and good data coverage. There is evidence of changes towards a worsened condition with stronger boreal influence, but the magnitudes of these changes are such that they are assessed to have overall limited impact on ecological condition. There are uncertainties related to the choice of category.	Based on the set of indicators this ecosystem characteristic is assessed as having ***limited deviation from the reference condition***. The assessment is based on 3 indicators with 3 associated phenomena with low to intermediate validity and intermediate to good data coverage. Increasing herbivore abundances, in particular populations of Arctic geese, cause shifts in biomass ratios. There are uncertainties regarding the choice of category especially due to absence of ground data that describes primary productivity/biomass of important foraging plants and vegetation types.
Functional groups within trophic levels	Based on the set of indicators the ecosystem characteristic is assessed as having ***limited deviation from the reference condition***. The assessment is based on 3 indicators with 3 associated phenomena with high validity and good data coverage. There is evidence of changes towards a worsened condition with stronger boreal influence, but the magnitudes of these changes are such that they are assessed to have overall limited impact on ecological condition.	Based on one indicator the ecosystem characteristic is assessed as having ***no deviation from the reference condition***. The assessment is based on 1 indicator with 1 associated phenomenon with intermediate validity and good data coverage. There is uncertainty related to choice of category, particularly due to absence of ground data that describes primary productivity/biomass of important foraging plants and vegetation types.
Functionally important species and biophysical structures	Based on the set of indicators the ecosystem characteristic is assessed as having ***limited deviation from the reference condition***. The assessment is based on 10 indicators with 13 associated phenomena with mainly high validity and good data coverage. There is evidence of changes towards a worsened condition with stronger boreal influence attributed to climate change, but the magnitudes of these changes are such that they are assessed to have overall limited impact on ecological condition. However, the ecotone portion of the ecosystem characteristic is assessed as having ***substantial deviations*** from the reference condition, primarily due to climate change intensified outbreaks by geometrid moth causing high forest and shrub mortality. There are uncertainties related to the choice of category.	Based on the set of indicators the ecosystem characteristic is assessed as having ***limited deviation from the reference condition***. The assessment is based on 6 indicators with 6 associated phenomena with low to intermediate validity and good data coverage. There is evidence of changes towards a worsened condition with impacts from herbivore grazing on tundra vegetation, but the magnitudes of these changes are such that they are assessed to still have overall limited impact on ecological condition. There are uncertainties related to the choice of category.

Continued: Summary of the condition assessments for each of the seven ecosystem characteristics of Low and High Arctic tundra

	Low Arctic tundra — Finnmark	High Arctic tundra — Svalbard
Landscape-ecological patterns	Based on the set of indicators the ecosystem characteristic is assessed as having ***substantial deviation from the reference condition***. The assessment is based on 3 indicators with 3 associated phenomena with intermediate validity and good data coverage. This is primarily due to a complete loss of areas which climatically belong to the Arctic bioclimatic subzone D (Southern Arctic tundra). Over time this transition towards a climate more indicative of shrub tundra or boreal forest will not permit the maintenance of structurally and functionally intact Low Arctic ecosystems. There are uncertainties related to the choice of category.	Based on the set of indicators the ecosystem characteristic is assessed as having ***substantial deviation from the reference condition***. The assessment is based on 2 indicators with 2 associated phenomena with high validity and intermediate data coverage. This is primarily due to an extensive loss of areas which climatically belong to the coldest Arctic bioclimatic subzone A (Arctic polar desert). There are uncertainties related to the choice of category.
Biological diversity	Based on the set of indicators the ecosystem characteristic is assessed as having ***substantial deviation from the reference condition***. The assessment is based on 7 indicators with 7 associated phenomena with intermediate validity and poor (for Arctic, endemic species) to good data coverage. Several Arctic species are critically endangered (Arctic fox) or absent in expected breeding years (snowy owl). Low Arctic bird and plant communities show an increasing degree of climate change related borealisation, especially for the bird community the rate of change is fast. The observed changes point to a loss of integrity of the Low Arctic ecosystem.	Based on the set of indicators the ecosystem characteristic is assessed as having ***no deviation from the reference condition***. The assessment is based on 1 indicator with 1 associated phenomenon with intermediate validity and good data coverage. There are uncertainties related to the choice of category, especially since the assessment is based on only one indicator (Svalbard ptarmigan breeding abundance), and due to the lack of important indicators for Arctic ecosystems (i.e. plant, bird, and insect communities).
Abiotic factors	Based on the set of climate related indicators the ecosystem characteristic is assessed as having ***substantial deviation from the reference condition***. The assessment is based on 11 indicators with 11 associated phenomena with intermediate to high validity and mainly good data coverage. The observed changes are dramatic and have occurred over the entire Low Arctic tundra and the ecotone. Several indicators are close to or exceed the historical observed variation during the reference period, in other words, values which during the 1961–1990 period were considered extreme are now within the expected norm.	Based on the set of indicators the ecosystem characteristic is assessed as having ***substantial deviation from the reference condition***. The assessment is based on 9 indicators with 10 associated phenomena with intermediate to high validity and good data coverage. The observed changes are dramatic and have occurred over the entire High Arctic tundra. Several indicators are close to or exceed the historical observed variation during the reference period, in other words, values which during the 1961–1990 period were considered extreme are now within the expected norm.

The condition of the ecosystem as a whole

Based on the overall assessment of the seven ecosystem characteristics, the scientific panel concludes that both sub-ecosystems in the Norwegian Arctic tundra show ***limited deviation*** from the reference condition. This means that most of the Arctic tundra ecosystems are still in ***good ecological condition*** with important functions and structures mainly maintained. The biotic changes that have occurred are mainly driven by climate change, which is happening fast in the Norwegian Arctic. This is evident in the present assessments as ***substantial deviations*** from the reference condition. However, also biotic ecosystem characteristics show deviations from the reference condition that are mainly consistent with phenomena driven by climate change. This particularly concerns the Low Arctic sub-ecosystem, which should be considered a warning of more extensive incipient ecosystem changes.

The Arctic tundra ecosystem is fundamentally contingent on the bioclimatic conditions that provide the foundation for species, communities, and food webs, and their ecological functions and diversity. In the Low Arctic, an entire bioclimatic subzone has vanished, in the sense that areas which during the reference period corresponded to the climatic definition of the coldest Low Arctic subzone (subzone D), now climatically correspond to the warmest Low Arctic subzone (subzone E), while areas previously located within the climatic definition of subzone E now are warmer than this (e.g. boreal). Similar shifts in bioclimatic subzones are also occurring in the High Arctic, but methodical challenges associated with the modelled climate data make it more challenging to estimate the area loss of High Arctic subzones. However, the rates of change in abiotic conditions in the High Arctic are more dramatic than in the Low Arctic. For instance, the indicator *Mean annual temperature* suggests a rate of change since the climatic reference period of around or above 1°C/decade for the High Arctic, which is almost twice the estimate for the Low Arctic.

These dramatic changes in abiotic conditions can be expected to result in biotic state changes. The Low Arctic tundra has continuous ecotones (borders) towards alpine and boreal systems, while the High Arctic tundra in Svalbard is isolated by ocean. Spread and establishment of boreal species in the Low Arctic tundra ecosystem can hence be expected to occur at a faster rate than the equivalent spread of Low Arctic species into High Arctic tundra ecosystem in Svalbard. This is in accordance with the observed changes in this assessment, where several biotic characteristics in the Low Arctic ecosystem show more substantial deviations from the reference condition than their High Arctic counterparts. However, it should be noted that the indicator coverage of several of the ecosystem characteristics is poorer in the High Arctic than in the Low Arctic (Table 7.3.2a, b).

The ecosystem characteristic *Primary productivity* is predicted to increase. Accordingly, Low Arctic and High Arctic tundra show a significant tendency for greening. However, this tendency is spatial heterogeneous and area restricted. Hence, the changes in *Primary productivity* are assessed as still limited. Simultaneous opposing changes in winter climate can counteract the increase in primary production, for instance through winter damage to the vegetation causing browning or large scale geometrid moth outbreaks (only in Finnmark). The deviations found in *Functionally important species and biophysical structures* are in accordance with phenomena linked to climate change, but mostly limited. However, some of the deviations are deemed substantial. Especially, the Low Arctic tundra-forest ecotone is substantially impacted by outbreaks of geometrid moths leading to reduction of forested areas and cascading negative effects on other functionally important species such as willow ptarmigan. Attention should be paid to some of the indicators/phenomena of *Functionally important species and biophysical structures* because they are related to management. In the Low Arctic, this applies to red fox and large carnivores because of their important functions as predators, and large herbivores (reindeer) based on their central position in the food web. In the High Arctic, the large increase in abundance of medium herbivores (geese) should be in focus, although grazing impacts are still deemed to be of limited ecosystem significance.

The ecosystem characteristic *Biological diversity* is assessed as having substantial deviation in the Low Arctic tundra. This assessment is partly due to the status of single species, such as the Arctic fox and snowy owl that are endemic to Arctic regions and/or red-listed, or the rapidly vanishing diversity of bird communities that characterise the Low Arctic tundra. These indicators are not representative of the biological diversity in the entire ecosystem, which emphasises the need of giving this ecosystem characteristic a better indicator coverage. At the same time, these indicators represent typical Arctic species that are high in the food web (i.e. carnivores and insectivores) and sensitive to changes (e.g. indirect effects due to trophic cascades), especially at the edges of their distribution ranges. Changes in their abundances or demography can therefore be early warnings of incipient ecosystem state changes. The comprehensive Low Arctic bird community indicator shows that a proportion of open tundra species declines fast — a decline consistent with recent findings in alpine ecosystems in Fennoscandia (Lehikoinen et al. 2014, Lehikoinen et al. 2019). The poor indicator coverage of *Biological diversity* in High Arctic Svalbard (with presently only one species included) should be noted.

Future trajectories for ecosystem condition

The pace of climate change is currently rapid in the Norwegian Arctic — emphasised by the substantial changes in the abiotic indicators for Low and High Arctic tundra ecosystems. In these tundra ecosystems, climate change is the most influential anthropogenic driver compared to other drivers, such as technical infrastructure, area loss and habitat fragmentation, harvesting, and natural resource management. Of these drivers, loss of habitat and fragmentation due to infrastructure are the drivers with less relevance in Arctic tundra today, while the other drivers are important drivers of the indicators in this assessment. Climate change dominates among the influencing factors highlighted in this assessment, which reflects that this anthropogenic impact not only contributes to the overall load, but in many cases dominates it, both directly and indirectly through interactions with others, and more manageable drivers, such as hunting.

The rate of change in the bioclimatic decisive indicator, *July mean temperature,* in the three decades after the climate reference period has been in the range of -0.2–0.7°C/decade in the low Arctic and 0.3–1.1°C/decade in the High Arctic. Similarly, snow cover duration in the Low Arctic tundra has decreased in the order of three weeks over the last three decades. In the High Arctic tundra, permafrost temperatures have increased by close to 1.0°C/decade since the monitoring was initiated. If this current pace of change continues, which is likely (Hanssen-Bauer et al. 2019, Hanssen-Bauer et al. 2015, IPCC 2020), the tundra sub-ecosystems subjected to the present assessment will in a few decades be far beyond the climate envelopes of their reference conditions. This is because ecosystems subjected to strong driver pressures are likely to show a mixture of fast and slow (time-lagged) responses in the state variables (Williams et al. 2021). Some responses will be highly non-linear or strongly interacting in a manner that can cause surprising overall state shifts or long-term transient states (CAFF 2013, Hastings et al. 2018, Ims and Yoccoz 2017, Lindenmayer et al. 2011, Planque 2016). Despite these limitations, PAEC provides means for predicting future ecosystem conditions on a short time horizon. This is because the phenomena specified for each indicator represent qualitative predictions of near-term trajectories of change (5–10 years). Collectively, the empirically supported phenomena in this assessment demonstrate that the Low Arctic Finnmark is presently subjected to a rapid borealisation of the ecosystem.

The statistical time series analyses yield rate-of-change estimates that in principle can be used for quantitative extrapolation in terms of future trajectories and states of the indicators (see Pedersen et al. 2021).

Research and monitoring recommendations

Following from the hierarchical structure of a PAEC assessment, the need for further research and monitoring is also highlighted in a hierarchical manner, from the specific needs to improve the weakest parts of the knowledge base for indicators, both in terms of better understanding and better data, to the overall recommendations for how the basis for the next assessment may be better than the current one. The key recommendations from the scientific panel are summarised as follows:

- The continued development of existing indicators, as well as the formulation of new recommended indicators, should be guided by the best empirical knowledge formulated as plausible hypotheses regarding drivers, ecosystem processes and trends, as also recommended by international assessments.
- Predictable funding of ecosystem-based adaptive monitoring programmes is a prerequisite for the continuation of the time series and other data sources upon which the assessment of the ecological condition in Arctic tundra currently rests.
- A list of identified indicators which are recommended to add in the future, is included. Some can be added with a limited effort, while others, such as pollinators, are omitted from current research and monitoring efforts in Norwegian Arctic ecosystems.
- Decomposition, which is a central ecosystem function especially in boreal and Arctic ecosystems, should be included as an eighth ecosystem characteristics in the *System for Assessment of Ecological Condition.*
- The use of new efficient technologies, such as ground (automatic sensors) and remotely (drones, satellites) based technologies, should be intensified to increase the scope of field measurements and improve the spatial coverage of indicators beyond what is possible based on field data alone. However, there is a substantial effort involved in consolidating sensor-based data to ecosystem processes occurring on the ground, which should not be overlooked. Field studies, sensor-based data and modelling efforts, for spatial extrapolation and for disentangling multi-driver impacts on ecological condition (e.g. quantitative ecosystem models), must therefore go hand in hand.
- For ecosystems undergoing rapid change, such as Arctic tundra ecosystems, there is a particular need for adaptive protocols and continuous development work to keep up with the fast, emerging challenges.
- Increased research on the causal links between ecosystem indicators and their combined stressors is needed to improve our understanding of the implications of changes in indicators for ecosystem condition.

The Norwegian Arctic tundra ecosystems show **limited deviation** from the reference condition. This means that most of the Arctic tundra ecosystems are still in **good ecological condition** with important functions, structures, and productivity mainly maintained. Photos: J. Stien/UiT (upper), R.A. Ims/UiT (lower)

Sammendrag

System for vurdering av økologisk tilstand, koordinert av Miljødirektoratet, skal utgjøre fundamentet for en kunnskapsbasert vurdering av økologisk tilstand for norske terrestre og marine økosystemer som ikke er omfattet av vanndirektivet. Denne rapporten beskriver den første operasjonelle vurderingen av arktiske tundraøkosystemer i Norge – høyarktisk tundra på Svalbard og lavarktisk tundra i Finnmark. Tilstandsvurderingen følger metoden *Panel-basert vurdering av økosystemtilstand* (Panel-based Assessment of Ecosystem Condition [PAEC]; Jepsen et al. 2020).

Sentrale rammer for vurderingen

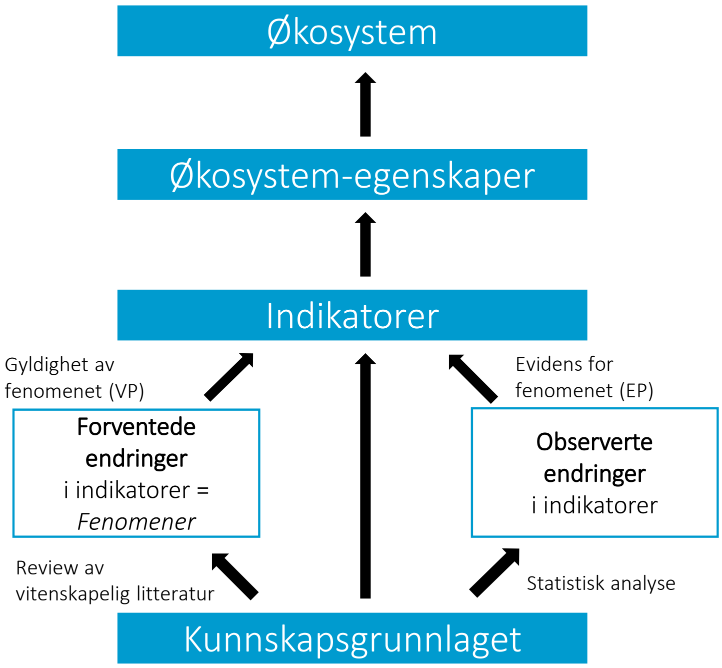
Tilstandsvurderingen av arktisk tundra følger rammene for *System for vurdering av økologisk tilstand* slik de er definert i Nybø & Evju (2017). Det anbefales der at tilstandsvurderingen adresserer syv konkrete økosystemegenskaper hvor hver av dem er representert ved et sett av abiotiske og/eller biotiske indikatorer. Referansetilstanden, som man vurderer dagens tilstand mot, er definert som "*intakte økosystemer*" karakterisert ved at økosystemets økologiske strukturer, funksjoner og produktivitet er ivaretatt. Dette innebærer at økosystemets struktur og funksjon ikke er vesentlig påvirket av menneskelige aktiviteter. Det defineres videre en klimatisk referanse som tilsvarer klimaet beskrevet for normalperioden 1961–1990 (se kap. 2 for hele definisjonen fra Nybø & Evju 2017).

Overordnede konklusjoner fra tilstandsvurderingen av arktisk tundra

- Arktiske tundraøkosystemer i Norge har, siden den klimatiske referanseperioden (1961–1990), opplevd betydelige endringer i de abiotiske forholdene. Disse endringene er tydelige og demonstrert særlig gjennom økende temperaturer, lengere vekstsesong, kortere sesong med snø og oppvarming og tining av permafrost.
- De økologiske/biotiske konsekvensene av endringene for økosystemene er foreløpig begrensede, og tydeligst for økosystemegenskaper (*Landskapsøkologiske mønstre* og *Biologiske mangfold*) og indikatorer (f.eks. bioklimatiske soner, arktiske og endemiske arter, plantesamfunn) som har sterkest kopling til klima som påvirkningsfaktor.
- Fagpanelet konkluderer dermed at norske arktiske tundraøkosystemer er i god tilstand der fundamentale økologiske strukturer og funksjoner i hovedsak fortsatt er ivaretatt på tross av store abiotiske endringer. Imidlertid viser også biotiske økosystemegenskaper avvik fra referansetilstanden og er på en endringsbane som bør betraktes som et varsel om at større innebygde endringer er under utvikling. Lavarktisk tundra i Finnmark viser mer omfattende og konsistente endringer enn høyarktisk tundra på Svalbard. I Finnmark er tundraøkosystemet i ferd med å tape typiske arktiske arter (fjellrev og snøugle) og bioklimatisk er tundraen på vei fra lavarktiske til boreale soner.

Grunnleggende prinsipper i PAEC

PAEC er en strukturert protokoll for vurdering av økosystemtilstand relativt til en referansetilstand. Protokollen er hierarkisk, og vurderingene bygges gradvis opp fra en vurdering av det tilgjengelige kunnskapsgrunnlaget gjennom formulering av forventede endringer i indikatorer (fenomener) og en evaluering av observerte endringer i indikatorer basert på statistisk analyse, til en helhetlig vurdering av tilstanden for hver av sju økosystemegenskaper og for økosystemet som helhet (se figur).



En skjematisk oppsummering av hierarkiet i en tilstandsvurdering etter PAEC (Jepsen et al. 2020). De fire primære nivåer i PAEC (blå bokser) er vurderinger av 1) kunnskapsgrunnlaget, 2) tilstanden til individuelle indikatorer, 3) tilstanden til økosystemegenskaper, og 4) tilstanden til økosystemet som helhet. Vurderingen av individuelle indikatorer baserer seg på i hvilken grad observerte endringer, avdekket ved statistisk analyse (endringsrater) av datagrunnlaget, er i samsvar med de forventede endringer (uttrykt i fenomenene).

Formuleringen av fenomener er avgjørende i PAEC. Fenomenene spesifiserer årsakssammenhenger mellom indikatorer og relevante påvirkningsfaktorer på økosystemets struktur, funksjon og produktivitet, basert på publisert vitenskapelig litteratur (se eksempler under). Disse årsakssammenhengene er beskrevet som kvalitative prediksjoner (hypoteser) om hvilke retningsbestemte endringer man forventer i en indikator, samt deres sannsynlige betydning for økosystemets tilstand. Fenomenenes gyldighet (VP) uttrykker hvor sikker man er på disse prediksjonene, basert på tilgjengelig vitenskapelig litteratur, mens statistisk analyse av de underliggende data avgjør i hvilken grad observerte endringer er i tråd med de oppsatte prediksjonene (EP – evidens for fenomenene).

Sentralt i PAEC er også fokus på de ulike kildene av usikkerhet i de tilgjengelige datasettene og hvordan disse påvirker vurderingene. Kildene til usikkerhet kan bare vurderes kvantitativt på én måte; ved å estimere konfidensintervallet for endringsraten til indikatoren basert på statistisk tidsserie-analyse av overvåkingsdata. Romlige og tidsmessige komponenter i datadekning av indikatorer, samt indikatordekning av de syv økosystemegenskapene, må vurderes kvalitativt, men basert på et strengt sett med kriterier definert av den tekniske protokollen for PAEC (Jepsen et al. 2020).

Tilstandsvurderingene i PAEC gjøres av et vitenskapelig fagpanel. Fagpanelet for arktisk tundra i 2020 besto av 20 forskere med ekspertise på økosystemets egenskaper, samt påkrevde analytiske metoder for å vurdere endringer i disse. PAEC-protokollen (Jepsen et al. 2020) gir detaljerte instrukser om hvordan hvert enkelt stadium i vurderingen skal gjennomføres og dokumenteres, fra den innledende kartleggingsfasen, gjennom dataanalysen, til den helhetlige vurderingen og rapporteringen. Dette inkluderer definisjoner av vurderingskategorier for de ulike nivåer i vurderingen.

Eksempler på indikator/fenomen for lavarktisk tundra og høyarktisk tundra.

Lavarktisk tundra

Indikator: Tetthet av lirype

Fenomen: Lave eller minkende bestander av lirype.

Forklaring: Klimaendringer påvirker direkte tetthet av lirype negativt gjennom sesongmessige endringer og økte nedbørsmengder i kritiske perioder. Fravær av smågnagersykluser, endret predasjonstrykk og jakt påvirker også bestandstallene.

Høyarktisk tundra

Indikator: Dødelighet av svalbardrein

Fenomen: Høy eller økende dødelighet for svalbardrein.

Forklaring: Svalbardreinens dødelighet er tett koplet til tetthet i bestanden og værforholdene om vinteren. I vintre med mye is på bakken som blokkerer mattilgangen for reinen, og særlig under høy bestandstetthet, øker dødeligheten.

Foto: G. Vie/UiT (ø. venstre), E. Fuglei/NP (ø. høyre), M.A. Strømseng/UiT (n. venstre), J. Kohler/NP (n. høyre)

Datasett og indikatorer anvendt i vurderingen

Den helhetlige vurderingen av økologisk tilstand for norsk arktisk tundra bygger på analyser av 34 datasett (kap. 3) som understøtter 16 indikatorer felles for begge deløkosystemer, 26 indikatorer som er unike for lavarktisk tundra og åtte indikatorer som er unike for høyarktisk tundra (kap. 4). Den største andelen av datasettene hentes fra det økosystembaserte *Klima-økologisk Observasjonssystem for Arktisk Tundra* (COAT) og *Miljøovervåking Svalbard og Jan Mayen* (MOSJ), begge dedikert til overvåking av arktiske økosystemer, samt fra Meteorologisk Institutts landsdekkende klimadataservice. Det samlede indikatorsettet dekker alle syv økosystemegenskaper i begge deløkosystemer, men indikatordekningen (vurdert til tre kategorier) varierer fra begrenset dekning ("Inadequate") til dekkende ("Adequate") for ulike egenskaper og er generelt bedre for lavarktisk tundra enn for høyarktisk tundra.

Hovedparten av de biotiske datasettene dekker en tidsperiode på 15–30 år, mens de klimatiske datasettene dekker 60 år; den klimatiske referanseperioden (1961–1990; definert i grunnlaget for *System for vurdering av økologisk tilstand,* se kap. 2) samt den etterfølgende 30-års perioden (1991–i dag). Datadekningen (som vurderes til fire kategorier avhengig av romlig og tidsmessig representativitet for datasettet, Tabell 7.1a, b) er bedre for lavarktisk tundra (90 % av indikatorer vurdert til de to høyeste kategorier "Very good" og "Good") enn for høyarktisk tundra (67 % av indikatorer vurdert til de to høyeste kategorier).

Vurdering av tilstand for økosystemegenskaper

De syv økosystemegenskapene som er under betraktning i *System for vurdering av økologisk tilstand* er: *Primærproduksjon, Biomasse mellom trofiske nivåer, Funksjonelle grupper innen trofisk nivå, Funksjonelt viktige arter og biofysiske strukturer, Landskapsøkologiske mønstre, Biologisk mangfold og Abiotiske forhold* (se kap. 2 for en normativ beskrivelse av referansetilstanden for hver økosystemkarakteristikk). Økologisk tilstand for hver økosystemegenskap vurderes til en av tre kategorier med økende avvik fra referansetilstanden — fra ingen til betydelige avvik fra referansetilstanden (se definisjoner under). Kategoritilhørighet er primært avhengig av vurderingen av gyldigheten (VP; basert på vitenskapelig litteratur) og beviset (EP; har endringen skjedd) for de underliggende fenomenene. Et fenomen er en beskrivelse av forventninger, såkalte vitenskapelige hypoteser, til hvordan hver indikator endrer seg mot dårligere tilstand som følge av påvirkning fra de menneskeskapte driverne i økosystemet. Økosystemegenskaper som vurderes til ***begrenset avvik*** fra referansetilstanden, viser endringer som indikerer at de er på en endringsbane bort fra et intakt økosystem. Økosystemegenskaper som vurderes til ***betydelig avvik*** fra referansetilstanden kan ikke lenger betraktes representative for et intakt økosystem.

Forkortet definisjon av de tre vurderingskategoriene. For full beskrivelse se kap.7.3 og Jepsen et al. (2020).

Ingen avvik fra referansetilstanden
En økosystemegenskap i denne kategorien er samlet sett vurdert som i god økologisk tilstand basert på det gjeldende indikatorsettet. Den viser ingen eller svært begrensede avvik fra referansetilstanden.

Begrensende avvik fra referansetilstanden
En økosystemegenskap i denne kategorien er samlet sett vurdert som i god økologisk tilstand, basert på det gjeldende indikatorsettet. Egenskapen viser imidlertid avvik fra referansetilstanden, som tyder på en utvikling mot dårligere tilstand.

Betydelige avvik fra referansetilstanden
En økosystemegenskap i denne kategorien er samlet sett vurdert som i dårlig økologisk tilstand, basert på det gjeldende indikatorsettet. Egenskapen viser betydelige avvik fra referansetilstanden.

Basert på vitenskapelig gyldighet og bevis for underliggende fenomener knyttet til indikatorene er fagpanelets konklusjoner for hver økosystemkarakteristikk oppsummert nedenfor for begge deløkosystemene.

For **lavarktisk tundra i Finnmark** viser alle økosystemegenskaper avvik fra referansetilstanden, enten i begrenset eller betydelig grad (se definisjoner under og kap. 7.3). Fire egenskaper (*Primærproduksjon, Biomasse mellom trofiske nivåer, Funksjonelle grupper innen trofisk nivå, Funksjonelt viktige arter og biofysiske strukturer*) viser ***begrenset avvik*** ("Limited deviation"), mens tre egenskaper (*Landskapsøkologiske mønstre, Biologisk mangfold, Abiotiske forhold*) viser ***betydelig avvik*** ("Substantial deviation").

For **høyarktisk tundra på Svalbard** viser to økosystemegenskaper (*Funksjonelle grupper innen trofisk nivå, Biologisk mangfold*) ingen avvik fra referansetilstanden, mens de andre fem egenskapene viser enten i begrenset eller betydelig grad avvik (se definisjoner under og kap. 7.3). Tre egenskaper (*Primærproduksjon, Biomasse mellom trofiske nivåer, Funksjonelt viktige arter og biofysiske strukturer*) viser ***begrenset avvik*** ("Limited deviation"), mens to (*Landskapsøkologiske mønstre, Abiotiske forhold)* viser ***betydelig avvik*** ("Substantial deviation").

Oppsummering av tilstandsvurderingene for hver av de syv økosystemkarakteristikkene for lav- og høyarktisk tundra.

	Lavarktisk tundra — Finnmark	Høyarktisk tundra — Svalbard
Primærproduksjon	Økosystemegenskapen viser ***begrenset avvik fra god økologisk tilstand***. Vurderingen er basert på 3 indikatorer med 3 tilhørende fenomener av høy gyldighet og med god datadekning. Det er bevis på endringer mot en forverret tilstand i samsvar med fenomener som tilskrives klimaendringene, men størrelsen på disse endringene er foreløpig små og/eller varierende slik at de vurderes til å ha begrenset innvirkning på den økologiske tilstanden.	Økosystemegenskapen viser ***begrenset avvik fra god økologisk tilstand***. Vurderingen er gjort basert på 2 indikatorer med 2 tilhørende fenomener av høy gyldighet og med god datadekning. Det er bevis på endringer mot en forverret tilstand i samsvar med fenomener som tilskrives klimaendringene, men størrelsen på disse endringene er foreløpig små og/eller varierende slik at de vurderes til å ha begrenset innvirkning på den økologiske tilstanden.
Biomasse mellom trofiske nivåer	Økosystemegenskapen viser ***begrenset avvik fra god økologisk tilstand***. Vurderingen er basert på 4 indikatorer med 4 tilhørende fenomener av middels til høy gyldighet og med god datadekning. Det er bevis på endringer mot en forverret tilstand med sterkere boreal innflytelse i samsvar med fenomener som tilskrives klimaendringene, men størrelsen på disse endringene er vurdert til å ha begrenset innvirkning på den økologiske tilstanden. Det er usikkerhet knyttet til valg av kategori.	Økosystemegenskapen viser ***begrenset avvik fra god økologisk tilstand***. Vurderingen er gjort basert på 3 indikatorer med 3 tilhørende fenomener av lav til middels gyldighet og middels til god datadekning. Økende bestander av plantespisere, spesielt bestander av arktiske gjess, forårsaker endringer i biomasseforholdene. Det er usikkerhet angående valg av kategori, særlig grunnet fravær av bakkedata som beskriver planteproduksjon/biomasse av viktige beiteplanter og vegetasjonstyper.
Funksjonelle grupper innen trofisk nivå	Økosystemegenskapen viser ***begrenset avvik fra god økologisk tilstand***. Vurderingen er basert på 3 indikatorer med 3 tilhørende fenomener av høy gyldighet og med god datadekning. Det er bevis på endringer mot en forverret tilstand med sterkere boreal innflytelse, men størrelsen på disse endringene er vurdert til å ha begrenset innvirkning på den økologiske tilstanden.	Økosystemegenskapen viser ***ingen avvik fra god økologisk tilstand***. Vurderingen er gjort basert på 1 indikatorer med 1 tilhørende fenomen av middels gyldighet og med god datadekning. Det er usikkerhet angående valg av kategori, særlig grunnet fravær av bakkedata som beskriver planteproduksjon/biomasse av viktige beiteplanter og vegetasjonstyper.
Funksjonelt viktige arter og biofysiske strukturer	Økosystemegenskapen viser ***begrenset avvik fra god økologisk tilstand***. Vurderingen er gjort basert på 10 indikatorer med 13 tilhørende fenomener der de fleste har høy gyldighet og med god datadekning. Indikatorene representere et mangfold av økologiske funksjoner og strukturer. Det er bevis på endringer mot en forverret tilstand med sterkere boreal innflytelse i samsvar med fenomener som tilskrives klimaendringene, men størrelsen på disse endringene er foreløpig vurdert til å ha begrenset innvirkning på den økologiske tilstanden. Økotonen (overgangen mellom skog og tundra) er imidlertid vurdert til å ha betydelige avvik fra referansetilstanden, hovedsakelig på grunn av klimaendringer som fører til storskala målerutbrudd som forårsaker høy dødelighet av trær og busker. Det er derfor usikkerhet knyttet til valg av kategori.	Økosystemegenskapen viser ***begrenset avvik fra god økologisk tilstand***. Vurderingen er gjort basert på 6 indikatorer med 6 tilhørende fenomener av lav til middels gyldighet og middels til god datadekning. Indikatorene representere et mangfold av økologiske funksjoner og strukturer. Det er bevis på endringer mot en forverret tilstand som følge av intensivert beite fra plantespisere, særlig arktiske gjess, på tundravegetasjonen. Foreløpig er størrelsen på disse endringene vurdert til å ha en begrenset innvirkning på den økologiske tilstanden. Det er usikkerhet angående valg av kategori, særlig grunnet fravær av bakkedata som beskriver planteproduksjon/biomasse av viktige beiteplanter og vegetasjonstyper.

Fortsettelse: Oppsummering av tilstandsvurderingene for hver av de syv økosystemkarakteristikkene for lav- og høyarktisk tundra.

	Lavarktisk tundra — Finnmark	Høyarktisk tundra — Svalbard
Landskapsøko-logiske mønstre	Økosystemegenskapen viser ***betydelig avvik fra god økologisk tilstand***. Vurderingen er gjort basert på 3 indikatorer med 3 tilhørende fenomener av middels gyldighet og med god datadekning. Den dårlige tilstanden skyldes et fullstendig tap av områder som klimatisk tilhører den arktiske bioklimatiske delsonen, sørarktisk tundrasone (sone D). Hele den lavarktiske tundraen befinner seg klimatisk sett i dag i kratttundra (sone E). På sikt vil dette klima ikke opprettholde struktur, funksjon og produksjon som karakteriserer intakte lavarktiske økosystemer. Det er usikkerhet knyttet til valg av kategori.	Økosystemegenskapen viser ***betydelig avvik fra god økologisk tilstand***. Vurderingen er gjort basert på 2 indikatorer med 2 tilhørende fenomener av høy gyldighet og med middels datadekning. Den dårlige tilstanden skyldes et fullstendig tap av områder som klimatisk tilhører den høyarktiske bioklimatiske delsonen, arktisk polarørken (sone A). Det er usikkerhet knyttet til valg av kategori grunnet fravær av indikatorer som beskriver erosjon og vegetasjonsskader.
Biologisk mangfold	Økosystemegenskapen viser ***betydelig avvik fra god økologisk tilstand***. Vurderingen er gjort basert på 7 indikatorer med 7 tilhørende fenomener av middels gyldighet og med datadekning som varierer fra dårlig (arktiske, endemiske arter) til god. Flere karakteristiske arktiske arter er kritisk truet (fjellrev) eller er fraværende i år der det var forventet reproduksjon (snøugle). Lavarktiske fugle- og plantesamfunn viser en økende grad av påvirkning/innfluks av arter som karakteriserer boreale økosystemer som en følge av klimaendringer. Endringer er særlig påfallende og raske for fuglesamfunnet er. De observerte endringene peker på et tap av integritet i det lavarktiske økosystemet.	Økosystemegenskapen viser et ***ingen avvik fra god økologisk tilstand***. Vurderingen er gjort basert på 1 indikator med 1 tilhørende fenomen av middels gyldighet og med god datadekning. Det er usikkerhet angående valg av kategori, særlig fordi vurderingen er basert bare på en indikator (hekketetthet av svalbardrype), og at det mangler indikatorer for viktige komponenter i arktiske økosystemer (f.eks. plante- og fuglesamfunn og insekter).
Abiotiske forhold	Økosystemegenskapen viser ***betydelig avvik fra god økologisk tilstand***. Vurderingen er gjort basert på 11 indikatorer med 11 tilhørende fenomener av middels til høy gyldighet og med datadekning som stort sett er god. De observerte endringene er dramatiske og har skjedd over hele den lavarktiske tundraen og tilhørende overgangssone mot skog (økoton). Flere indikatorer er nær eller overgår den historiske observerte variasjonen i referanseperioden (1961-1990). Dette betyr at verdier som i referanseperioden ble ansett som ekstreme, er nå innenfor den forventede normen av verdier.	Økosystemegenskapen viser ***betydelig avvik fra god økologisk tilstand***. Vurderingen er gjort basert på 9 indikatorer med 10 tilhørende fenomener av middels til høy gyldighet og med datadekning som stort sett er god. De observerte endringene er dramatiske og har skjedd over hele den høyarktiske tundraen. Flere indikatorer er nær eller overgår den historiske observerte variasjonen i referanseperioden (1961-1990). Dette betyr at verdier som i referanseperioden ble ansett som ekstreme, er nå innenfor den forventede normen av verdier.

Vurdering av tilstand for økosystemene som helhet

Basert på tilstandsvurderingen av de syv økosystemegenskapene, konkluderer fagpanelet med at begge deløkosystemer i norsk arktisk tundra viser ***begrensede avvik*** fra referansetilstanden. Dette betyr at de arktiske tundraøkosystemene fremdeles er i ***god økologisk tilstand*** der de viktigste funksjoner og strukturer er ivaretatt. De observerte biotiske endringer er primært drevet av raske klimaendringer, som i denne vurderingen er dokumentert i form av ***betydelige avvik*** fra referansetilstanden. Flere av de biotiske økosystemkarakteristikkene viser også avvik fra referansetilstanden, særlig de som har indikatorer og tilhørende fenomener drevet av klimaendringene. Dette gjelder spesielt for lavarktisk Finnmark der endringene kan betraktes som varsler om forestående endringer i økosystemets tilstand.

Det arktiske tundraøkosystemet er fundamentalt avhengig av de bioklimatiske forholdene som gir grunnlaget for arter, samfunn og næringsnett og deres økologiske funksjoner og mangfold. I lavarktis har en hel bioklimatisk undersone forsvunnet. Dette betyr at arealer som under den klimatiske referanseperioden (1961–1990) klimatisk sett tilhørte den kaldeste lavarktiske undersone (D), nå tilsvarer den varmeste lavarktiske sone (E). Tilsvarende endringer har skjedd i høyarktisk tundra, men metodiske utfordringer gjør det vanskeligere å estimere arealtapet. Imidlertid er hastigheten på endringene i abiotiske forhold på Svalbard mer dramatiske enn i Finnmark. Dette er spesielt tydelig for indikatoren, *Gjennomsnittlig årstemperatur,* der endringsraten siden den klimatiske referanseperioden er på 1°C/tiår for høyarktisk tundra noe som er nesten dobbelt så høyt som for den lavarktiske tundraen.

Slike drastiske endringer i abiotiske forhold kan forventes å forårsake en rekke biotiske tilstandsendringer. Den lavarktiske tundraen har kontinuerlige økotoner (grenser) mot alpine og boreale systemer, mens den høyarktiske tundraen på Svalbard er isolert av havet. Spredning og etablering av boreale elementer i det lavarktiske tundraøkosystemet kan derfor forventes å forekomme raskere i Finnmark enn på Svalbard. Dette samsvarer med de observerte endringene i vurderingen, der flere biotiske økosystemegenskaper i lavarktisk tundra avviker fra referansetilstanden enn i høyarktisk tundra. I denne forbindelse er det viktig å påpeke at indikatordekningen for flere av økosystemets egenskaper er dårligere på Svalbard enn i Finnmark (se tabell 7.3.2a, b).

Økosystemkarakteristikken *Primærproduksjon* antas å øke. Følgelig viser både lavarktisk og høyarktisk tundra en betydelig tendens til grønning selv om den er romlig heterogen og arealbegrenset. Derfor vurderes endringene i primærproduksjonen fremdeles som begrenset. Samtidig foregår endringer i vinterklimaet som kan motvirke økningen i primærproduksjonen dersom f.eks. vinterskader på vegetasjonen forårsaker «bruning» (vegetasjonsdød) eller storskala målerutbrudd som følge av klimadrevet spredning (kun i Finnmark). Avvikene i økosystemegenskapen *Funksjonelt viktige arter og biofysiske strukturer* er i samsvar med fenomener knyttet til klimaendringer, men fortsatt stort sett begrenset. Likevel, noen av avvikene er betydelige. Dette gjelder spesielt for økotonen i lavarktisk der storskala målerutbrudd fører til reduksjon av skog- og buskkledde områder og negative effekter på andre funksjonelt viktige arter som f.eks. lirype. Slike endringer må betraktes som en indikasjon på begynnende tilstandsendringer. Det bør også rettes oppmerksomhet mot noen av indikatorene/fenomenene til denne økosystemegenskapen, *Funksjonelt viktige arter og biofysiske strukturer,* fordi de er relatert til forvaltning. I lavarktisk tundra gjelder dette for eksempel rødrev og store rovdyr, som har viktige funksjoner som rovdyr, og store plantespisere (reinsdyr) som har en sentral posisjon i næringsnettet. I høyarktisk tundra bør økningen av gjess (middels store planteetere) være i fokus, selv om beiteeffekter fremdeles anses å være av begrenset betydning for økosystemet.

Økosystemkarakteristikken *Biologisk mangfold* viser betydelig avvik i lavarktisk tundra. Vurderingen er hovedsakelig basert på statusen til enkeltarter (fjellrev og snøugle), som er karakteristiske for lavarktisk tundra og/eller rødlistet, eller raskt forsvinnende mangfold av fuglesamfunn som kjennetegner den lavarktiske tundraen. Disse indikatorene er ikke representative for det biologiske mangfoldet i hele økosystemet, noe som understreker behovet for en bedre indikatordekning. Samtidig representerer indikatorene typiske arktiske arter, høyt i næringsnettet og som er følsomme for klimaendringer (f.eks. indirekte effekter på grunn av trofiske kaskader), spesielt i yttergrensen av sitt utbredelsesområde. Endringer i antall eller demografi kan derfor være tidlige varsler om begynnende tilstandsendringer i økosystemet. Indikatoren for lavarktisk fuglesamfunn viser at andelen åpne tundraarter synker raskt — en nedgang som samsvarer med funn fra andre alpine økosystemer i Fennoskandia (Lehikoinen et al. 2014, Lehikoinen et al. 2019). Den dårlige indikatordekningen av det biologiske mangfoldet på Svalbard (per i dag kun Svalbardrype) bør bemerkes.

Vurdering av fremtidig utvikling i økosystemtilstand

Norsk Arktis er utsatt for raske klimaendringer — noe som understrekes av de betydelige endringene i alle de abiotiske indikatorene for både høy- og lavarktiske tundraøkosystemer. I disse tundraøkosystemene er klimaendringene den største menneskelige driver sammenliknet med andre påvirkninger som f.eks. arealinngrep, habitatfragmentering, høsting og forvaltning. Av disse er arealinngrep den påvirkningsfaktor som per i dag har minst relevans for tundra, mens alle de øvrige inngår som viktige påvirkningsfaktorer av de respektive indikatorer. Når klimaendringer dominerer blant påvirkningsfaktorer som fremheves i vurderingen, avspeiler dette at denne påvirkningsfaktoren i dag ikke bare bidrar til den samlede belastningen, men i mange tilfeller dominerer den samlede belastningen, både direkte og gjennom sterk samvirkning (interaksjoner) med andre og mer lokale forvaltningsbare påvirkningsfaktorer, som f.eks. jakt.

Endringsraten i den bioklimatisk avgjørende indikatoren, *Gjennomsnittlig julitemperatur* (indikator *Mean July temperature*), i de tre tiårene etter den klimatiske referanseperioden, har vært i størrelsesorden -0.2–0.7°C/tiår i lavarktisk tundra og 0.3–1.1°C/tiår i høyarktisk tundra. I samme periode har den snødekte sesongen (indikator *Snow cover duration*) blitt rundt tre uker kortere. I høyarktisk tundra har permafrosttemperaturen økt med i underkant av 1 grad/tiår siden målingene begynte. Hvis de nåværende endringsrater fortsetter, vil begge deløkosystemer i løpet av få tiår være langt utenfor de klimatiske rammer som definerer referansen for denne vurderingen (Hanssen-Bauer et al. 2019, Hanssen-Bauer et al. 2015). Slike sterke påvirkninger gir opphav til en blanding av raske og trege (tidsforsinkede) økologiske responser med innvirkninger på økosystemtilstand (Williams et al. 2021). Noen vil være ikke-lineære, eller ha sterke interaksjoner, som kan resultere i overraskende tilstandsendringer eller langvarige forbigående («transiente») tilstander. Prognoser for den sannsynlige endringsbanen til arktiske økosystemer i et langtidsperspektiv er dermed ikke mulig. Fenomenene som formuleres i PAEC representerer imidlertid kvalitative prediksjoner om endringsbaner for indikatorer og dermed samlet sett for den økologiske tilstanden i et kortsiktig perspektiv (f.eks. 5–10 år). Samlet sett demonstrerer de at lavarktiske tundraøkosystemer er utsatt for en raskt økende påvirkning fra sørlige/boreale arter (såkalt borealisering). I denne sammenheng kan statistiske modeller som omfatter ulike drivere av endringer være spesielt nyttige for å forutsi og validere hvordan forvaltning kan modifisere negative endringsbaner. Slike modeller kan dermed bidra til å utvikle forvaltningsstrategier med mål om å redusere endring mot forverret økologisk tilstand (se Pedersen et al. 2021).

Anbefalinger for forskning og overvåking

I likhet med den hierarkiske strukturen i PAEC, adresseres også kunnskapsbehovet og anbefalinger for videre forskning og overvåking på flere nivåer, fra spesifikke behov for videreutvikling og forbedringer av kunnskapsgrunnlaget (bedre data og bedre forståelse av konkrete indikatorers rolle for økologisk tilstand), til overordnede anbefalinger for hvordan grunnlaget for neste vurdering kan bli bedre enn dagens. De mest sentrale anbefalingene fra fagpanelet oppsummeres som følger:

- Videreutvikling av eksisterende indikatorer, så vel som formulering av nye anbefalte indikatorer, bør styres av best mulig empirisk kunnskap formulert som hypoteser («prediksjoner») om sammenhengen mellom påvirkningsfaktorer, økologiske prosesser og endringsrater, noe som også er anbefalt i internasjonale utredninger.
- Forutsigbar finansiering av integrert overvåking av sentrale komponenter i næringsnettet på tundraen (såkalt økosystem-basert) i et adaptivt rammeverk der det tas høyde for raske miljøendringer (særlig fra klimaendringene) er en forutsetning for videreføring av tidsserier og andre datakilder som den nåværende vurdering av økologisk tilstand i Arktisk tundra bygger på.
- En liste med sentrale indikatorer, anbefalt for inkludering i fremtiden, er identifisert. Noen kan inkluderes med en begrenset innsats, mens andre, eksempelvis pollinatorer, ikke er inkludert i dagens forskning og overvåking i norske arktiske økosystemer og mangler dermed datagrunnlag.
- Nedbryting er en sentral økosystemfunksjon særlig tilknyttet karbonbudsjettet i boreale og arktiske økosystemer, som bør inkluderes som en åttende økosystemegenskap i *System for vurdering av økologisk tilstand*.
- Bruk av ny og effektiv teknologi, både bakkebasert (automatiske sensorer) og fjernmålingsbasert (droner, satellitter), bør intensiveres for å forbedre den romlige dekningen av indikatorer ut over det som er mulig å oppnå basert på manuelle bakkemålinger alene. Det er imidlertid betydelige utfordringer og arbeid involvert i å konsolidere sensorbaserte data med økosystemprosesser på bakken, som ikke bør bli oversett. Bakkestudier, fjernmåling og modellutvikling, både for romlig ekstrapolering og for å skille effekter av flere drivere og samlet belastning på økologisk tilstand, må derfor gå hånd i hånd.
- For økosystemer som er utsatt for svært store menneskelige påvirkninger som gir raske endringer, slik som arktisk tundra, er det et spesielt behov for adaptive protokoller og et kontinuerlig utviklingsarbeid for å holde tritt med utfordringene.
- Økt forskning på koplingen (årsak–virkning) mellom indikatorer og deres samlede påvirkningsfaktorer er viktig for å få en bedre forståelse av hvordan endringer i indikatorer påvirker økosystemtilstand.

De norske arktiske tundraøkosystemene viser **begrenset avvik** fra referansetilstanden. Dette betyr at norsk arktisk tundra fremdeles er i **god økologisk tilstand** der viktige funksjoner, strukturer og produktivitet i hovedsak fortsatt er ivaretatt. Foto: R.A. Ims/UiT (over), N. Lecomte/Université de Moncton (under).

Introduction

Mandated by the Norwegian Ministry of Climate and Environment, the *System for Assessment of Ecological condition*[1] was destined — for each of the nation's major terrestrial and marine ecosystems not covered by the EU Water Framework Directive — to 1) define criteria for what could be considered good ecological condition and 2) develop methods for assessing the degree of deviation from "good condition" (Nybø and Evju 2017). Two alternative assessment methods have been developed (Jakobsson et al. 2021, Jepsen et al. 2020). The background for developing *Panel-based Ecosystem Assessment of Ecosystem Condition* (PAEC) is an increasing demand for integrated assessments of the condition of entire ecosystem units under intensified anthropogenic pressures. PAEC is inspired by approaches used in several national and international bodies, including the *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES 2020), *Intergovernmental Panel on Climate Change* (IPCC 2020) and the *French national ecosystem assessment* (EFESE 2020). These bodies share the common notion that the condition or state of complex systems (e.g. climate systems, ecosystems), and the level of evidence for change in the condition of such systems as a result of anthropogenic and natural drivers, are best assessed by broad scientific panels following stringent and structured protocols.

PAEC is a structured protocol for a panel-based assessment of the condition of an ecosystem relative to a specific reference condition (Jepsen et al. 2020). It is a goal that PAEC should provide a framework for making reproducible qualitative assessments based on solid quantitative analyses of the underlying data. The assessment is made in a hierarchical manner and consists of four phases; 1) *Scoping*, 2) *Analysis*, 3) *Assessment,* and 4) *Reporting and peer review* (Fig. 1). Key to the *Scoping Phase*, is the formulation of specific formalised expectations (termed *Phenomena*) describing expected directional changes in a given indicator or state variable as a result of relevant drivers acting on the system. Phenomena are thus the equivalent of a scientific hypothesis formulated prior to a scientific study. The *Analysis Phase* consists of a statistical analysis of the underlying data to permit an assessment of the level of evidence for each phenomenon. The *Assessment Phase* consists of a plenary session where the assessment panel scrutinises and assesses the knowledge base underlying the assessment, assesses the condition of each of a set of *ecosystem characteristics* covering structural and functional components (biotic and abiotic) of the ecosystem, and finally assesses the condition of the entire ecosystem. An independent *Peer review* of the final assessment report with the aim of continuous improvements is a fundamental step in PAEC.

An assessment according to PAEC is primarily a scientific exercise, and the scientific assessment panel should consist of a group of scientists with in-depth knowledge of the focal ecosystem characteristics, as well as relevant quantitative methodology (study design and statistical modelling). However, PAEC is also envisioned to be a tool for adaptive management of ecosystems, or specific ecosystem components. Thus, the protocol allows for the integration of a stakeholder group (consisting for instance of representatives for management agencies responsible for the specific ecosystem) into the assessment process (Fig. 1). This is non-mandatory but may serve to broaden PAEC from a purely scientific assessment, to an operational and policy-relevant tool for developing management goals and adaptive management strategies for the implementation and assessments of specific management actions. Depending on the type of process in which the protocol is used, the level of stakeholder involvement in the assessment phase may vary across the different phases.

1 In Nybø and Evju (2017) termed *"Technical system for determining good ecological condition".*

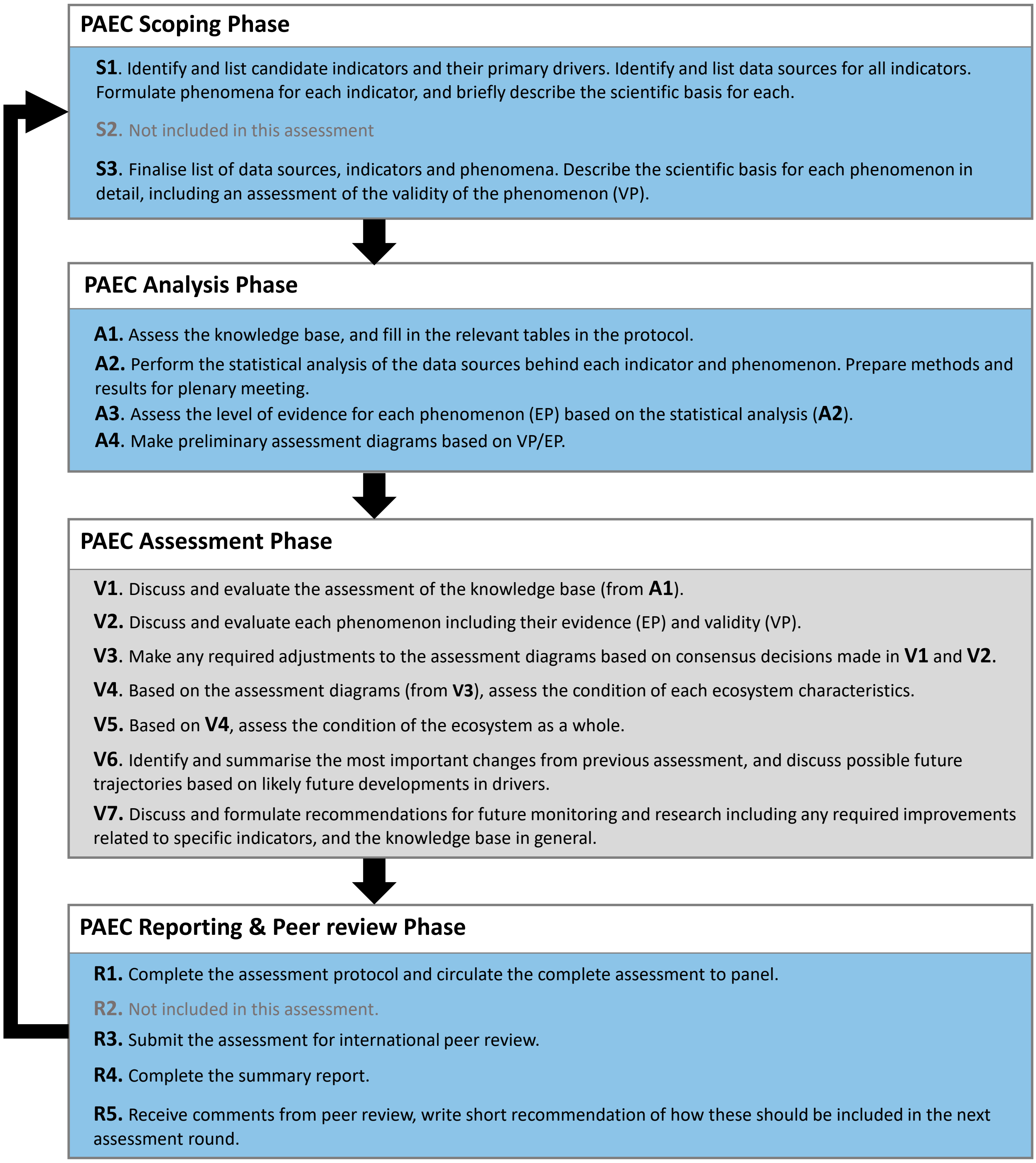


Figure 1. Summary of the four phases of ecosystem condition assessment according to PAEC, and the main tasks involved in each phase. PAEC allows non-mandatory involvement of a stakeholder group in the assessment panel in addition to the scientific panel. In such cases, the stakeholder group would provide input during the Scoping Phase (Task S2), participate in all or parts of the plenary assessment meeting (Tasks V1-V7), and provide comments on the assessment report prior to peer review (Task R2). Stakeholders were not involved in the tundra assessment, hence tasks S2 and R2 are not included. Revised from Jepsen et al. (2020).

Definitions of terms

Below we list terms and their definitions as described in Jepsen et al. (2020).

Term	Definition
Ecosystem characteristics	Characteristics of an ecosystem underlying how abiotic factors, ecosystem structure and functions interact. In the current assessment framework, seven characteristics are considered; primary productivity, biomass distribution among trophic levels, functional groups within trophic levels, functionally important species and biophysical structures, landscape-ecological patterns, biological diversity, and abiotic factors.
State variable	Ecosystem feature describing an ecosystem characteristic. A state variable measures directly the functions and processes of its corresponding ecosystem characteristic(s). State variables can be used to build models for estimating causal relations between ecosystem characteristics and external drivers and to make quantitative predictions across space and time. One state variable can be associated with more than one ecosystem characteristic.
Ecosystem condition	Describes the current state of the ecosystem across all ecosystem characteristics by summarising the state variables, often in terms of their dynamical regime. We consider here the term ecosystem condition to be synonymous with "ecosystem state". State is often used in the context of alternative states, when the ecosystem can shift between regimes that persist at a particular spatial extent and temporal scale, but state changes may also be gradual.
Reference condition	Describes the state of the ecosystem at a pre-defined time period (e.g. "a climatic reference period"), or according to specific criteria such as the absence of local and global human influences ("a pristine state"), or the maintenance of important functional or structural components (e.g., population cycles, "a functional ecosystem"). Such a reference condition is characterised by the range of variation and covariation among state variables due to ecosystem dynamics over a period that is long enough to get statistically reliable estimates, but with persistent (stable) environmental conditions.
Indicator	A preferably simple and easily interpreted surrogate for a state variable or a driver/pressure (the "canary in the mine"). Because indicators are required to have many properties (e.g. sensitive to changes, applicable over a large area, valid over a wide range of stress, cost-effective), a set of complementary indicators is often required. In this document the term indicator denotes all metrics that are used to describe the focal ecosystem characteristics. Accordingly, it is important to note that indicators may range from state variables that directly represent ecological functions and structures to surrogate indices that have more or less validated indirect relations to such functions and structures.
Ecosystem significance	A change in an indicator and its associated ecosystem characteristic is of ecosystem significance when the deviation from the reference condition implies ecologically large changes in the ecosystem characteristic the indicator is associated with or large changes to other ecosystem characteristics and to the ecosystem condition generally. This is not related to statistical significance.
Phenomenon	A phenomenon is an expected directional change in an indicator which is of ecosystem significance and which can be attributed to one or more relevant drivers. Phenomena are thus the equivalent of scientific hypotheses formulated prior to a scientific study.
Quantitative phenomenon	A phenomenon is quantitative if one can identify and estimate a threshold value for the change in the indicator which, if exceeded, results in a change away from the reference condition which is of ecosystem significance.

Qualitative phenomenon	A phenomenon is qualitative when one cannot identify and estimate such a threshold value, but rather focuses on the type and direction of changes away from the reference condition linked to drivers that can lead to changes of ecosystem significance.
Validity of phenomenon (VP)	Validity of a phenomenon addresses the links between drivers and ecosystem significance by assessing 1) how well we understand the mechanisms by which drivers affect an indicator, and 2) how well we understand how the change in an indicator leads to changes that are of ecosystem significance.
Evidence for phenomenon (EP)	Assessment of the quality of empirical evidence for 1) expected changes in an indicator has occurred (incl. statistical significance) and 2) that the change is of ecosystem significance. The assessment hence considers both the relationship between state variables and indicators, and between indicators and ecosystem condition. The assessment relies upon the consistency in observed changes (over space and time), and the uncertainty of the estimated changes. In particular, a distinction is made between the absence of evidence for a phenomenon due to large uncertainties, and evidence that no change of ecosystem significance has occurred.
Design-based sampling and estimation	Given that one can define a target population with a list of units, design-based sampling uses either probability sampling where the probability that each unit is sampled is known a priori (e.g. stratified sampling with more variable strata being sampled more intensively), or some form of systematic sampling (e.g. grid). In the former case, one can use the design to estimate parameters of interest (e.g. averages) with known uncertainty without relying on statistical models.
Model-based sampling and estimation	Model-based sampling aims at maximising the accuracy of estimates of relationships between predictors (e.g. drivers) and responses (e.g. ecosystem state variables). Designs combine precision of estimates by having large contrasts in predictor values and accuracy of the functional response by allowing for non-linear responses and sampling intermediate values of predictors. Model-based estimation uses the model to extrapolate to non-sampled units and is sensitive to the model used. Robustness needs to be evaluated.

A typical High Arctic landscape on the west coast of Svalbard with scarce plant cover and short ecological gradients. Photo: J. M. Mosbacher/NPI

1. Composition of the scientific panel

Below we list participants in the scientific panel assessment, as well as their respective roles and expertise (Table 1.1).

Table 1.1. The composition of the scientific panel with definitions of roles and expertise. The list is sorted alphabetically by surname, except for the panel leader who is listed first. HA = High Arctic, LA = Low Arctic.

Name, institution, email	Role	Expertise	Expert on single indicators
Åshild Ø. Pedersen, NPI [1] aashild.pedersen@npolar.no	**Project manager, leader of scientific panel,** expert	Svalbard reindeer, Svalbard rock ptarmigan, food web ecology (HA)	Svalbard reindeer (HI03, HI05, HI09-HI11) and Svalbard rock ptarmigan related indicators (HI15)
Hanna Böhner, UiT [2*] Hanna.bohner@uit.no	Expert, participant in scientific panel	Plant biomass, plant growth forms, food web ecology (LA)	Tundra plant related indicators (LI03, LI04, LI05, LI08, LI11, LI12, LI25)
Kari Anne Bråthen, UiT [2] kari.brathen@uit.no	Expert, participant in scientific panel	Plant biomass, plant growth forms, food web ecology (LA)	Tundra plant related indicators (LI03, LI04, LI05, LI08, LI11, LI12, LI25)
Dorothee Ehrich, UiT [2] dorothee.ehrich@uit.no	Expert, participant in scientific panel	Rodents, Arctic fox, red fox, food web ecology (LA)	Rodent and carnivore related indicators (LI06, LI07, LI10, LI14, LI20, LI25, LI26, LI27)
Eva Fuglei, NPI [1] eva.fuglei@npolar.no	Expert, participant in scientific panel	Svalbard rock ptarmigan, Arctic fox, food web ecology (HA)	Svalbard rock ptarmigan (HI15) and Arctic fox related indicators (HI05, HI12)
John-Andre Henden, UiT [2] john-andre.henden@uit.no	Expert, participant in scientific panel, statistical analyses	Willow and rock ptarmigan, Svalbard rock ptarmigan, food web ecology, (LA/HA)	Tundra bird related indicators (LI15, LI31)
Rolf A. Ims, UiT [2] rolf.ims@uit.no	Expert, participant in scientific panel, statistical analyses	Predators, rodents, food web ecology (LA)	Rodent and carnivore related indicators (LI06, LI07, LI10, LI20, LI28, LI29, LI30)
Ketil Isaksen, MET Norway [3] ketili@met.no	Expert, participant in scientific panel	Abiotic climatic indicators, permafrost (HA)	Climate related indicators in the High Arctic (HI16, HI17, HI20 HI22, HI23, HI24)
Simon Jakobsson, NINA [4] simon.jakobsson@nina.no	Expert, participant in scientific panel	Forest-tundra bird communities (LA)	Tundra bird related indicators (LI31)
Jane Uhd Jepsen, NINA [4] jane.jepsen@nina.no	Expert, participant in scientific panel, data management, statistical analyses	Forest-tundra ecotone, insect outbreaks (moth), food web ecology (LA)	Vegetation productivity related indicators (LI01, HI01, LI02, HI02), Mountain birch in forest-tundra (LI13), Bioclimatic subzones (LI23, HI13), Wilderness areas (LI24, HI14), Geometrid moth outbreaks (LI16)
Jesper Madsen, AU [5] jm@bios.au.dk	Expert, participant in scientific panel	Birds, pink-footed goose, barnacle goose, breeding phenology, adaptive management (HA)	Pink-footed goose and barnacle goose related indicators (HI04, HI05, HI07, HI08)
Jesper B. Mosbacher, NPI [1] jesper.mosbacher@npolar.no	Expert, participant in scientific panel	Food web ecology, ungulate (HA)	–

Table 1.1 continued.

Name, institution, email	Role	Expertise	Expert on single indicators
Ingrid M. G. Paulsen, NPI [1] ingrid.paulsen@npolar.no	Participant in scientific panel, data management, statistical analyses, secretariat	—	—
Virve Ravolainen, NPI [1] virve.ravolainen@npolar.no	Expert, participant in scientific panel	Plant biomass, plant growth forms food web ecology (HA)	Vegetation productivity and herbivore related indicators (LI01, HI01, LI02, HI02, HI03, HI04, LI05)
Eeva Soininen, UIT [2] eeva.soininen@uit.no	Expert, participant in scientific panel	Plant biomass, plant growth forms, rodents, food web ecology (LA)	Plant and herbivore related indicators (LI04, LI08, LI09, LI14, LI22)
Audun Stien, UiT [2] audun.stien@uit.no	Expert, participant in scientific panel	Semi-domestic reindeer, Svalbard reindeer, food web ecology (LA/HA)	Semi-domestic reindeer related indicators (LI05, LI07, LI09, LI17, LI18, LI19), Large predators (LI21), Svalbard reindeer related indicators (HI03, HI06, HI09, HI10, HI11, HI13)
Ingunn Tombre, NINA [4] ingunn.tombre@nina.no	Expert, participant in scientific panel	Barnacle goose and pink-footed goose (HA)	Barnacle goose and pink-footed goose related indicators (HI04, HI06-HI08)
Ole Einar Tveito, MET Norway [3] oleet@met.no	Expert, participant in scientific panel	Abiotic climatic indicators (LA)	Climate related indicators in the High Arctic (HI16-HI22, HI24) and Low Arctic (LI32-LI41)
Torkild Tveraa, NINA [4] torkild.tveraa@nina.no	Expert, participant in scientific panel	Semi-domestic reindeer, food web ecology (LA)	Semi-domestic reindeer related indicators (LI05, LI07, LI09, LI17, LI18, LI19), Large predators (LI21)
Ole Petter L. Vindstad, UiT [2] ole.p.vindstad@uit.no	Expert, participant in scientific panel	Forest-tundra ecotone, insect outbreaks (moth) (LA)	Vegetation productivity related indicators (LI01, LI02), Mountain birch in forest-tundra (LI13), Geometrid moth outbreaks (LI16)
Nigel Yoccoz, UiT [2] nigel.yoccoz@uit.no	Expert, participant in scientific panel, statistical analyses, data management,	Abiotic climatic indicators, rodents, food web ecology (LA)	Start of growing season (LI02), herbivore related indicators (LI06, LI09, LI14), Climate related indicators (LI32, LI33, LI38, LI39, LI41-LI42)
Ellen Øseth, NPI [1] ellen.oseth@npolar.no	Secretariat	—	—

[1]NPI — Norwegian Polar Institute, [2]UiT — UiT The Arctic University of Norway, [3]MET Norway — Norwegian Meteorological Institute, [4]NINA — Norwegian Institute for Nature Research, [5]AU — Aarhus University. * Böhner did not participate during the panel meeting 16–17 November 2020.

2. Definition of the reference condition

The common framework for all assessments of ecological condition made under the *System for Assessment of Ecological Condition* is defined in Nybø and Evju (2017). This includes the current assessment of Norwegian Arctic tundra ecosystems. In Nybø and Evju (2017), the reference condition is defined as "intact ecosystems", and the assessment should consider whether or not, or the extent to which, the current condition of the ecosystem and its components deviate from this reference condition. The term "good ecological condition" is here used to characterise a condition in which the structure, functions and productivity of an ecosystem do not deviate substantially from the reference condition.

In the following we first reiterate the complete definitions from Nybø and Evju (2017) of what constitutes an "intact ecosystem", and what climatic reference the assessment should be based on (Box 1). We further reiterate their normative description of the condition of each ecosystem characteristic under the reference condition (Box 2). Finally, we describe how these definitions have been incorporated in the current assessment of the ecological condition of Norwegian Arctic tundra ecosystems according to PAEC.

Box 1. Definitions from Nybø and Evju (2017) (our translations from Norwegian).

Intact ecosystems

Intact, natural, and semi-natural ecosystems are characterised by the maintenance of fundamental structures, functions, and productivity. Intact ecosystems are further characterised by having complete food webs, and element cycles. The majority of the food web consists of native species which dominate at all trophic levels and in all functional groups. The species composition, population structure and genetic diversity of native species are results of natural processes occurring through the ecological and evolutionary history of the ecosystem. Intact ecosystems possess characteristics which are not changing systematically over time but vary within the boundaries of the natural dynamics of the system.

Human influences can be present, but should not be pervasive or dominating, or be a factor which changes the structure, function or productivity of the ecosystem. This means that human influences should not be at a scale which exceeds the impacts of natural pressures (e.g. disturbance) or dominating species (e.g. top predators) in the ecosystem. Furthermore, human influences should not lead to changes which are more rapid or more pervasive than natural pressures in the ecosystem. In semi-natural ecosystems, the human activities which define the system (e.g. grazing, hay cutting) are considered an integral part of the ecosystem.

Reference climate

The climate used as a basis for the assessment of intact ecosystems is a climate as described for the climatic normal period 1961–1990.

Box 2. The normative description from Nybø and Evju (2017) of each of the seven ecosystem characteristics in "good ecological condition", i.e. when there are no substantial deviations from the reference condition (our translation from Norwegian).

Primary productivity: *The primary productivity does not deviate substantially from the productivity in an intact ecosystem. Reason: Elevated or decreased primary productivity indicates a system impacted for instance by eutrophication, overgrazing, or drought.*

Biomass distribution among trophic levels: *The distribution of biomass among trophic levels does not deviate substantially from the distribution in an intact ecosystem. Reason: Substantial shifts in biomass distribution between trophic levels indicate a system impacted for instance by removal of top predators.*

Functional groups within trophic levels: *The functional composition within trophic levels does not deviate substantially from the composition in an intact ecosystem. Reason: Substantial changes in the functional composition within trophic levels indicate a system impacted for instance by loss of functional groups (e.g. pollinators), loss of open habitat species due to encroachment, or super-dominance of certain functional groups or species (e.g. jellyfish in marine habitats).*

Functionally important species and biophysical structures: *The functions of functionally important species, habitat building species, and biophysical structures do not deviate substantially from the functions in an intact ecosystem. Reason: Functionally important species (e.g. small rodents), habitat building species (e.g. coral reefs, kelp forest), and biophysical structures (e.g. dead wood) are of vital importance for the population size of a number of species, and changes in their occurrence will hence have functional implications for the ecosystem.*

Landscape-ecological patterns: *Landscape-ecological patterns are compatible with the persistence of species over time, and do not deviate substantially from an intact ecosystem. Reason: Human influences can lead to changes in landscape-ecological patterns which have implications for the population size and population structure of native species, for instance through habitat fragmentation. Fragmented habitats may not be sufficiently large or connected to permit long-term survival of native species. Climate change, altered area use, pollution and invasive or introduced species may also influence landscape-ecological patterns with implications for population size and composition of native species.*

Biological diversity: *The genetic diversity, species composition, and species turnover do not deviate substantially from an intact ecosystem. Reason: Loss of biological diversity can cause the ecosystem to be less resilient towards pressures and disturbances, and influence the structure, functions and productivity of the ecosystem. Changes in rates of species turnover, due to extinction or colonisation can indicate a modified system.*[1]

Abiotic factors: *Abiotic condition (physical and chemical) does not deviate substantially from an intact ecosystem. Reason: Human influences (e.g. environmental toxins, fertilisation, changed hydrology or acidification) can lead to substantial changes in the physical/chemical structure and function of the ecosystem, which in turn will impact the species composition, function and dynamics of the ecosystem.*[2]

[1] Loss or decline of Arctic endemics or species which are typical for Arctic ecosystems is within this definition considered a deviation from an "intact Arctic ecosystem".

[2] Abiotic factors are in this context considered to include the climatic conditions under which the ecosystem exists, and climatically derived indicators, hence, included in the assessment of the ecosystem characteristic *Abiotic factors*.

Intact, natural and semi-natural, ecosystems are characterised by the maintenance of fundamental structures, functions and productivity (Nybø and Evju 2017). Photo: J. Iglhaut/NINA

The main implications of the above definitions (Box 1 and 2) for the current assessment of Norwegian Arctic tundra ecosystems are the following:

- In PAEC, the condition of the ecosystem, and its characteristics, are classified into categories, depending on the extent to which their current condition deviate from the reference condition. Following the definition of the reference condition in Box 1, the current assessment of Arctic tundra hence focuses on the extent to which the ecosystem and its components deviate from an intact ecosystem condition in which the structure, functions and productivity of the ecosystem is under no or limited influence from human pressures.
- The definition provided in Box 1 from Nybø and Evju (2017) for the ecosystem characteristic *Biological diversity* is considered to include Arctic endemic species or other species typical for Arctic tundra. Loss or decline of such species is interpreted as a deviation from an intact ecosystem.
- The driver–response relationships between indicators/state variables and pressures, focus on human pressures, which include climate change, and on identifying the impact of human pressures relative to natural variation in the ecosystem.
- Phenomena (see Definitions of Terms and Ch. 5) are formulated relative to the reference condition representing an "intact ecosystem" in Arctic tundra according to the definition in Box 1. This means that a given phenomenon describes the expected directional change away from an intact Arctic tundra ecosystem as a result of human pressures.
- For Arctic ecosystems, climate change is one of the most influential human pressures, and altered climatic conditions already have pervasive impacts on important structural and functional attributes of tundra ecosystems (CAFF 2013, 2017). Climatic indicators hence play an

important role in the assessment of the ecosystem characteristic *Abiotic factors* in the current assessment of Arctic tundra. In order to consider the given definition of the reference climate (Box 1), climate indicators are analysed and evaluated relative to the average and variability observed during the 1961–1990 climate normal period.

- PAEC requires that the assessment of temporal representativity (Ch. 7.1, Fig. 7.1) includes an evaluation of the extent to which data underlying the indicators are overlapping with any "temporally defined reference period" used. Consequently, the evaluation of temporal representativity of the data used in this assessment accounts for the extent to which the underlying data is overlapping with the climatic normal period 1961–1990. This does not imply that 1961–1990 is considered an "ecological reference period" as human influences could be extensive already during this time period or indeed much prior to it. However, it is of relevance to evaluate the extent to which the ecological and climatic data underlying the assessment, can in fact be considered representative for a climate corresponding to the 1961–1990 normal period. This is particularly true for Arctic ecosystems that already experience climatic conditions which are, in part, substantially different from the conditions before 1990 (Hanssen-Bauer et al. 2019, Hanssen-Bauer et al. 2015, Nordli et al. 2020).

The ecosystem characteristic Biological diversity includes Arctic endemic species or other species typical for Arctic tundra. Loss or decline of such species is interpreted as a deviation from an intact ecosystem. Photos : G. Vie/UiT (upper left), F. Sletten/NPI (upper right), N. Lecomte/Université de Moncton (lower left), T. Nordstad/NPI (lower right)

3. Ecosystem delineation, data sources, and choice and utility of indicators

3.1 Delineation of the ecosystem

The ecosystem under consideration here is Norwegian Arctic tundra. The ecosystem is divided into two subsystems: Low Arctic tundra, located exclusively on the Norwegian mainland, and High Arctic tundra, occurring exclusively in Svalbard. This assessment employs the same geographical delineation of the Arctic as is used in “Natur i Norge” (Halvorsen et al. 2016; herafter referred to as NiN). NiN is based on the five bioclimatic subzones in the Arctic defined in the circumpolar Arctic vegetation map (CAVM Team 2003; Table 3.1). On the Norwegian mainland, at least two subzones are represented (D and E) — here considered as Low Arctic. In Svalbard, there are three subzones (A, B and C) — here considered as High Arctic. These subzones are based on the geographic relationships between summer temperatures and the occurrence/distribution of functional plant groups.

The Norwegian Arctic tundra is characterised by treeless areas north of the timberline with average summer temperatures usually below 9-12°C. Photo: G. Vie/UiT

The *Arctic Biodiversity Assessment* (CAFF 2013) found that this vegetation-based classification could to some extent indicate the presence of functional groups at higher trophic levels, although there can be considerable large-scale geographic differences, probably owing to other abiotic variables, glaciation history, topography and land use. When using these subzones, it must therefore be kept in mind that circumpolar definitions do not necessarily apply locally. In NiN, all areas that are connected to areas north of the Arctic timberline, i.e. all areas from which it is possible to reach the coast without crossing forested land, are considered Arctic (Artsdatabanken 2020). This definition includes the Varanger, Nordkinn and Sværholt Peninsulas and Magerøya island in Low Arctic, Finnmark (Fig. 3.1a). The condition of Low Arctic tundra ecosystems is influenced by biotic processes in the adjacent forest-tundra ecotone. Examples of such processes are reindeer grazing and insect outbreaks that affect forest health and the characteristics and location of the tree line, and northward expansion of boreal species (Bråthen et al. 2007, Jepsen et al. 2009a). This assessment therefore includes a small set of indicators which capture forest-tundra ecotone processes of relevance to tundra ecosystems. It is not possible to set a definitive, biologically justified limit for the geographic scale on which such ecotone indicators should be assessed. In this assessment, the spatial extent of the forest-tundra ecotone is therefore defined by a fixed buffer zone extending 40 km south of the Low Arctic tundra. High Arctic tundra includes all of Svalbard, except Bjørnøya (Fig. 3.1b). In Svalbard, indicators based on full cover data sources (gridded climatic and satellite-based data), are calculated for each bioclimatic subzone to illustrate possible contrasts in indicator condition between subzones. On the mainland, such indicators are calculated separately for the Low Arctic tundra and the forest-tundra ecotone. Note that the size of the assessed tundra ecosystems differs substantially in terms of spatial extent, where High Arctic tundra is the largest (Fig. 3.1).

Tabell 3.1. The five circumpolar Arctic bioclimatic subzones. Based on average July temperature, summer warmth index, vertical structure of plant cover, horizontal structure of plant cover, major plant growth forms, dominant vegetation unit, total plant biomass, net annual production, and number of vascular plant species in local floras (CAVM Team 2003, Elvebakk 1994, Halvorsen et al. 2016).

CAVM subzone	NiN	Zone (Elvebakk 1994)	Mean July temperature
E	6SX–1	Arctic shrub–tundra zone (ASHTZ)	9–12°C
D	6SX–2	Southern Arctic tundra zone (SATZ)	7–9°C
C	6SX–3	Middle Arctic tundra zone (MATZ)	5–7°C
B	6SX–4	Northern Arctic tundra zone (NATZ)	3–5°C
A	6SX–5	Arctic polar desert zone (APDZ)	< 3°C

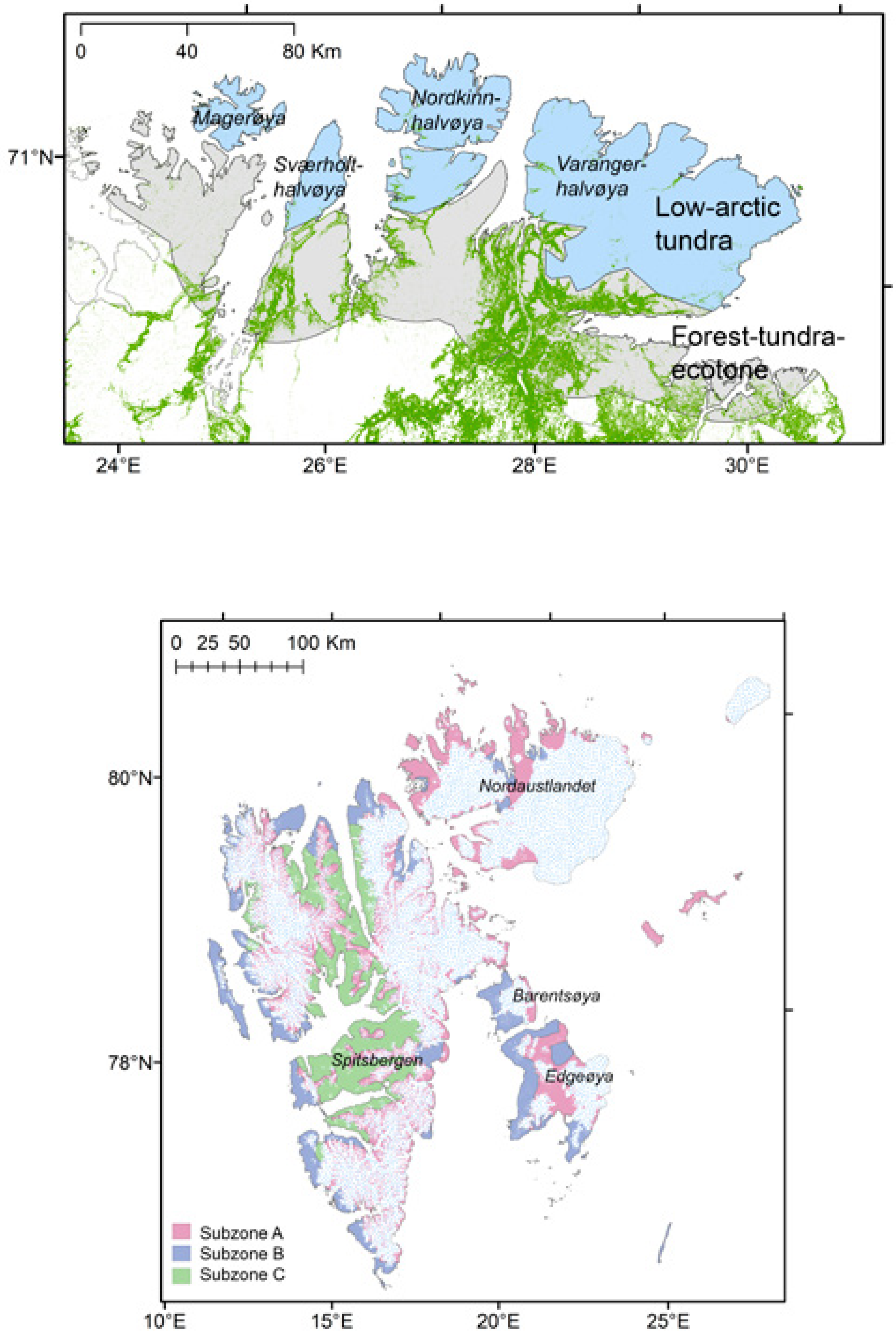


Figure 3.1. Maps showing the geographical delineation of the ecosystem. Upper panel: Geographical delineation of the area included in the assessment of Low Arctic tundra (blue) and the bordering forest-tundra ecotone (grey) in the county of Troms and Finnmark, mainland Norway. Forested areas are shown in green. Lower panel: Geographical delineation of the area included in the assessment of High Arctic tundra, which is divided in three bioclimatic zones. The entire archipelago of Svalbard, except Bjørnøya, is included in the assessment. Glaciers are shown as white, dotted areas.

3.2 General considerations regarding data sources

The datasets pertaining to Arctic tundra come from long-term thematic monitoring systems and programmes (Table 3.2a, b). Particularly, the *Climate-ecological Observatory for Arctic tundra* (COAT 2020) and the *Environmental Monitoring of Svalbard and Jan Mayen* (MOSJ 2020) are dedicated specifically to the monitoring of Norwegian Arctic ecosystems. COAT focuses on question-driven, adaptive monitoring of the effects of climate change on High and Low Arctic tundra ecosystems (Ims et al. 2013a, Ims and Yoccoz 2017). COAT derives key state variables listed in Table 3.2a, b. Close integration with natural resource management is central to COAT and is achieved, for example, through local reference groups, and testing of adaptive management measures (e.g. on Arctic fox and after moth outbreaks in forest-tundra ecotone). COAT Svalbard is a central component in the terrestrial part *Svalbard Integrated Arctic Earth Observing System* (SIOS). MOSJ has a broad focus on indicators of relevance for management of the atmosphere, land, and sea, including influential drivers/pressures such as fishing, travel/transport and pollution.

The spatial coverage of COAT and MOSJ determines the spatial coverage of major segments of the datasets that currently underlie indicators for tundra. The monitoring of terrestrial vertebrate species within MOSJ has focused mainly on areas near Longyearbyen and Ny-Ålesund, partly for logistical reasons. Consequently, the majority of the long field-based time-series are available only for the central valleys of Nordenskiöld Land and Brøggerhalvøya. Logistical and conservational constraints render it unlikely that the datasets for High Arctic tundra will ever become "area representative" *sensu stricto*; thus, the focus should be on achieving spatial representativeness by use of appropriate models that allow generalisation and extrapolation beyond the monitored areas. For this reason, PAEC requires that all datasets are assessed not only in terms of area representativeness, but also regarding whether the data allow model-based generalisations. COAT Svalbard is subject to the same logistical and geographical considerations as MOSJ and builds upon and complements the long-term monitoring in MOSJ. On the mainland, COAT builds upon years of research in eastern Finnmark, with a special focus on the Varanger Peninsula. The Low Arctic tundra and the associated ecotone towards the northern boreal forest (i.e. forest-tundra) have a smaller geographical extent than the land areas in Svalbard. In addition, there are fewer logistical constraints, which means greater possibilities for expansion of current monitoring and for independent testing of extrapolation of estimates from local model-based designs.

The temporal coverage of the datasets available for the assessment of Arctic tundra was assessed thoroughly in a previous report (section 3 in Jepsen et al. 2018). This assessment included whether the underlying data coincided with the last climatic normal period (1961–1990) chosen to be the climatic reference for all assessments (see Ch. 2), and, if not, whether it was collected during a period that deviated significantly from the climatic reference period. The conclusion was that, for most of the indicators, the data had little or no temporal overlap with the reference period, and that the climate prevailing at the time of data collection deviated significantly from that of the reference period, particularly for temperature. The underlying data must therefore be assumed to represent conditions that do not correspond to a 1961–1990 climate and which are already to greater or lesser degree affected by anthropogenic climate change.

The climate data applied for this assessment are gridded data. Gridded datasets are spatially continuous and represent climate variability in time and space. For the Low Arctic the indicators are based on SeNorge2 (Lussana et al. 2018a, Lussana et al. 2018b). This is a gridded dataset of mean daily temperature, daily precipitation and snow (water equivalent) with a spatial resolution 1×1 km, covering the period 1957 to present based on spatial analysis and interpolation of observations from in-situ weather stations.

For the High Arctic the weather station network is sparse, and gridded datasets based on observations are therefore not available. The indicators are consequently based on gridded datasets derived from downscaling of atmospheric reanalyses. The availability of long-term, updated gridded climate datasets with high resolution for this region is limited. In the assessment several datasets have therefore been applied, not necessarily giving consistent results. The Sval-Imp dataset (Østby et al. 2017, Schuler and Østby 2020) is a 1×1 km gridded dataset based on a downscaling of the ERA-40/ERA-interim global reanalyses, targeting representative climate data for glacier mass balance analysis. The dataset covers the period 1957–2017. The dataset has an issue with summer temperature due to parametrisation of the downscaling algorithm leading to unrealistic spatial variability when the ERA-temperatures are above the melting point. Sval-Imp will thus not provide representative summer temperatures. The increasing temperature in this region will enhance this effect. NORA3 is a 3×3 km hindcast dataset under development at MET Norway (Haakenstad et al. 2020) and investigated as a potential replacement for the Sval-Imp dataset. It applies the novel ERA5 global reanalysis (Hersbach et al. 2020) as boundary conditions, and covers the time period 1998–present, with some time gaps. In the current assessment the Sval-Imp and NORA3 datasets are used to assess High Arctic climate indicators.

Substantial investments are currently being made in the construction of the COAT data portal, which will manage COAT's data and the state variables derived from them, as well as making them available for the public, resource management, and monitoring programmes. The data portal will be operational by 2021. Many of COAT's key state variables are included as indicators in this assessment.

3.3 Choice and utility of indicators

The seven ecosystem characteristics underlying the assessment of ecosystem condition cannot be measured directly using a few variables as they themselves reflect complex components of the structure and function of ecosystems. Using indicators, surrogates or proxies is a common practice in ecology, and various frameworks have been proposed to develop and assess the utility of such indicators (e.g. Lindenmayer and Likens 2011, Noss 1990). Among the important trade-offs and components of indicators that have been emphasised (Lindenmayer et al. 2015), we have focused on: 1) Their scientific validity with regards to the characteristic, which component(s) of the characteristic is associated with the indicator, and its importance for the characteristic (the "objective" of the indicator), 2) the existence of a well-founded conceptual model linking what the indicator represents, its changes and the causal links to drivers (the "phenomenon"), 3) the comparison of different indicators in terms of uncertainty and spatio-temporal sampling (the "robustness" of an indicator). Criteria such as simplicity — an important aspect for communication or engaging stakeholders — were considered in a way similar to the use of models in science, that is simplifying without compromising their utility with regards to the objective. A common thread in recent reviews (Lindenmayer 2020, Lindenmayer and Westgate 2020) is the lack of empirical and theoretical evidence for the utility of indicators, and our choice of indicators aims to address these two aspects.

Norwegian Arctic tundra is divided into two subsystems — the Low Arctic tundra, located on the Norwegian mainland (upper), and the High Arctic tundra, occurring in Svalbard (lower).
Photos: G. Vie/UiT (upper), C. Jaspers/NPI (lower)

Table 3.2a. Description of data sources for assessment of ecological condition in Low Arctic tundra. The COAT Data Portal opened late 2020, and new datasets are added progressively. * Will be included in COAT Data Portal, data.coat.no

Dataset name	Dataset ID	Dataset DOI/URL	Owner institution	Contact person for data	Content and methods	Temporal coverage
MODIS EVI	LD01	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	Torkild Tveraa, NINA	EVI every 16 days through the whole year with 250x250 m resolution based on MODIS product MOD13Q1 (Huete et al. 2002).	2000–2019
Vascular plant biomass and richness in heath and meadow	LD02	Meadow https://data.coat.no/dataset/v_meadow_vascular_plant_abundance_observational_v3, Heath https://data.coat.no/dataset/v_heath_vascular_plant_abundance_observational_v3	UiT The Arctic University of Norway	Kari Anne Bråthen, UiT	Standing biomass and species richness of vascular plants in tundra vegetation types (heath and meadow), estimated annually in the middle of the growing season (Bråthen et al. 2007, Soininen et al. 2018).	2005–2020
Vascular plant cover in snowbeds	LD03	*	UiT The Arctic University of Norway	Eeva Soininen, UiT	Cover of a selection of vascular plants in tundra vegetation type, snowbed, estimated annually in the beginning of the growing season.	2009–2020
Rodent capture (intensive)	LD04	https://data.coat.no/dataset/v_rodents_snaptrapping_abundance_intensive_v3	UiT The Arctic University of Norway	Eeva Soininen, UiT	The number of different species of small mammals in primary tundra in heath and meadow vegetation (Soininen et al. 2018).	2005–2020
Rodent capture (regional)	LD05	https://data.coat.no/dataset/v_rodents_snaptrapping_abundance_regional_v2	UiT The Arctic University of Norway	Dorothee Ehrich, UiT	The number of different species of small mammals in primary tundra vegetation types (Soininen et al. 2018).	2004–2020
Semi-domestic reindeer regional statistics	LD06	reinbase.no/nb-no/Studer-reindriften/Reintall	Reinbase.no managed by Norwegian Institute for Nature Research	Audun Stien, UiT	The number of semi-domestic reindeer, calf slaughter weights and number of calves per adult female reindeer per district (Tveraa et al. 2013).	1981–2019

Table 3.2a. Continued.

Dataset name	Dataset ID	Dataset DOI/URL	Owner institution	Contact person for data	Content and methods	Temporal coverage
Incidental moose observations (“sett elg”)	LD07	https://hjorteviltregis-teret.no/Statistikk/Elg/Sett/Sett?Gruppering=0	Hjortevilt.no managed by Norwegian Institute for Nature Research	Erling Solberg, NINA	The number of moose seen, including age groups and sex, per municipality (Solberg et al. 2014)	2000–2019
Arctic fox den monitoring	LD08	–	Norwegian Environment Agency	Dorothee Ehrich, UiT National numbers available at State of the Environment Norway www.environment.no (data are partly excluded from the public)	Annual monitoring of known Arctic fox dens in management and reference areas for registration of occurrence of breeding, including minimum litter size. Red fox culling occurs in the management areas (Ims et al. 2017a).	1999, 2001–2020
Fox camera trap observations	LD09	*	UiT The Arctic University of Norway	Dorothee Ehrich, UiT	Camera traps deployed in late winter at carcass stations in management and reference areas. Red fox culling occurs in the management areas (Ims et al. 2017a).	2005–2020
Raptor breeding abundance	LD10	*	UiT The Arctic University of Norway	Rolf Anker Ims, UiT	Mapping of nests in fixed monitoring areas (Ims et al. 2017a).	2005/06–2020
Estimated willow ptarmigan densities	LD11	www.gbif.org/dataset/c47f13c1-7427-45a0-9f12-237aad351040	UiT The Arctic University of Norway	John-Andre Henden, UiT	Willow ptarmigan density per area unit based on survey of set lines (Nilsen et al. 2020) (Nilsen et al. 2020). Density is estimated based on distance sampling methodology (Fuglei et al. 2019a, Henden et al. 2020).	2000–2019
Ptarmigan fecal pellet presence	LD12	*	UiT The Arctic University of Norway	John-Andre Henden, UiT	Presence–absence of ptarmigan pellets in small quadrats. 8–12 plots of 50×50 cm placed systematically within each 15×15 m sampling square (Henden et al. 2011).	2005–2020

Table 3.2a. Continued.

Dataset name	Dataset ID	Dataset DOI/URL	Owner institution	Contact person for data	Content and methods	Temporal coverage
Geometrid moth (in birch forest)	LD13	*	Norwegian Institute for Nature Research, University of Turku, Finland	Jane Uhd Jepsen, NINA Kai Ruohomäki, University of Turku	Counts of geometrid moth larvae on birch at fixed monitoring sites that are visited annually. 10 replicated sites along a 2 km transect at each of 4 locations covering key climate-productivity gradients in Varanger Peninsula (COAT data) and a single point estimate at each of additional 4 locations (Klemola et al. 2006).	1987–2020 (Klemola et al. 2006) 2015–2020 (COAT data)
Geometrid moth dataset (in willow tundra)	LD14	*	Norwegian Institute for Nature Research	Jane Uhd Jepsen, NINA	Counts of geometrid moth larvae on willow at fixed monitoring sites that are visited annually. 28 replicated sites along a 40 km transect from Vadsø to Komagvær.	2019–2020
Mountain birch density in forest-tundra	LD15	www.doi.org/10.5061/dryad.1nm650h	Norwegian Institute for Nature Research	Jane Uhd Jepsen, NINA	Tree density, tree health, and recruitment along fixed monitoring transects located in forest with different degree of impact from moth outbreaks (Jepsen et al. 2013, Vindstad et al. 2019).	2010, 2016
Size of wilderness area	LD16	https://kartkatalog.geonorge.no/?text=villmark	Norwegian Environment Agency	–	Fully covered dataset with area loss of intact nature per status-year based on evaluation of distance from larger technical installations (INON 2020).	1988, 1998, 2003, 2008, 2013 and 2018
Bird community abundance and species richness	LD17	–	UiT The Arctic University of Norway	John-Andre Henden, UiT	Abundance per species from point-transect surveys in July with 3–4 repetitions in tundra habitats (Henden et al. 2013). Species richness is estimated using occupancy/N-mixture models.	2005–2016
Large predators	LD18	–	Rovdata.no managed by Norwegian Institute for Nature Research	Audun Stien, UiT	Total number of female wolverines with reproductive success in Finnmark, as observed through censuses of known dens and search for new dens in the period from March and into the summer (Overvåking – jerv 2021). Number of wolves as detected by snow tracks and genetic analyses of hair and faeces samples (Overvåking – ulv 2021).	2000–2020

Table 3.2a. Continued**.**

Dataset name	Dataset ID	Dataset DOI/URL	Owner institution	Contact person for data	Content and methods	Temporal coverage
Temperature	LD19	DOI: https://doi.org/10.5281/zenodo.845733 (1959-2015) URL: https://thredds.met.no/thredds/catalog/senorge/seNorge2/provisional_archive/catalog.html (1959-2020)	Norwegian Meteorological Institute	Ole Einar Tveito, MET	Daily gridded data with 1×1 km spatial resolution (Lussana et al. 2018a, Lussana et al. 2018b).	1957–2019/2020
Precipitation	LD20	DOI: https://doi.org/10.5281/zenodo.845733 (1959-2015) URL: https://thredds.met.no/thredds/catalog/senorge/seNorge2/provisional_archive/catalog.html (1959-2020)	Norwegian Meteorological Institute	Ole Einar Tveito, MET	Daily gridded data with 1×1 km spatial resolution (Lussana et al. 2018a, Lussana et al. 2018b).	1957–2019
Snow cover	LD21	DOI: https://doi.org/10.5281/zenodo.845733 (1959-2015) URL: https://thredds.met.no/thredds/catalog/senorge/seNorge2/provisional_archive/catalog.html (1959-2020)	Norwegian Meteorological Institute	Ole Einar Tveito, MET	Daily gridded data with 1×1 km spatial resolution (Lussana et al. 2018a, Lussana et al. 2018b).	1957–2020
Snow profiles	LD22	*	UiT The Arctic University of Norway	Nigel G. Yoccoz, UiT	Annual snow profiles in ticket meadow and heath habitats with measurements of snow depth, layer structure, and hardness/thickness per layer.	2006–2020

Table 3.2b. Description of data sources for assessment of ecological condition in High Arctic tundra. The COAT Data Portal opened late 2020, and new datasets are added progressively. * Will be included in COAT Data Portal, www.data.coat.no

Dataset name	Dataset ID	Dataset DOI/URL	Owner institution	Contact person for data	Content and methods	Temporal coverage
MODIS EVI	HD01	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	Torkild Tveraa, NINA	EVI every 16 days through the whole year with 250×250 m resolution based on MODIS product MOD13Q1 (Huete et al. 2002).	2000–2019
Svalbard reindeer population abundance and calf rates	HD02	http://www.mosj.no/en/fauna/terrestrial/svalbard-reindeer-population.html *	Norwegian Polar Institute	Åshild Ø. Pedersen, NPI Audun Stien, NINA	Annual census of Svalbard reindeer in summer (Adventdalen and Reindalen) and winter (Brøggerhalvøya) in fixed monitoring areas. Number of calves per female from summer counts in Adventdalen, Brøggerhalvøya (Aanes et al. 2003, Hansen et al. 2019b, Hansen et al. 2019a).	1978/79–2020
Svalbard reindeer carcass abundance	HD03	https://data.coat.no/dataset/s_ungulates_carcasses_adventdalen_summer_v3	Norwegian Polar Institute	Åshild Ø. Pedersen, NPI	Number of carcasses in summer census in Adventdalen (1991–present; Hansen et al. 2013, Peeters et al. 2017).	1979/1991–2020
Pink-footed goose spring population census	HD04	https://www.sciencebase.gov/catalog/item/5cc8890ee4b09b8c0b77f1cd	Aarhus University	Jesper Madsen, AU	Estimated median population abundance from an integrated population model, based on spring stating counts (Johnson et al. 2020).	1993–2020
Barnacle goose wintering population census	HD05	–	Wildfowl & Wetlands Trust (WWT), UK	Larry Griffin, WWT	Annual population numbers based on counts in the wintering areas in UK (Musgrove et al. 2011, Wildfowl and Wetlands Trust 2017).	1988–2020
Arctic fox den monitoring	HD06	http://www.mosj.no/en/fauna/terrestrial/arctic-fox-population.html *	Norwegian Polar Institute	Eva Fuglei, NPI (data are partly excluded from the public)	Annual monitoring of known Arctic fox breeding dens for registration of occurrence of breeding (Eide et al. 2012, Fuglei et al. 2003, Hansen et al. 2013, Nater et al. 2021).	1993/97–2019

Table 3.2b. Continued

Dataset name	Dataset ID	Dataset DOI/URL	Owner institution	Contact person for data	Content and methods	Temporal coverage
Svalbard rock ptarmigan breeding abundance	HD07	https://data.coat.no/dataset/s_ptarmigan_counts_v3	Norwegian Polar Institute	Eva Fuglei, Åshild Ø. Pedersen, NPI	Density of territorial males in spring from point transect sampling surveys on fixed monitoring locations (Marolla et al. 2021, Pedersen et al. 2012, Soininen et al. 2016).	2000–2019
Size of wilderness areas	HD08	https://kartkatalog.geonorge.no/?text=villmark	Norwegian Environment Agency	Ragnvald Larsen, Norwegian Environment Agency	Datasets covering the entire Svalbard archipelago with area loss of intact nature per status-year evaluated from distance from larger technical installations (INON 2020)	1990; 2015; 2019
Temperature	HD09	Sval-Imp: https://doi.org/10.11582/2018.00006 NORA3: Will become available at MET Norway	Norwegian Meteorological Institute	Ole Einar Tveito, MET	The Sval-Imp dataset with 1×1 km resolution based on ERA40 and ERA Interim (Østby et al. 2017, Vikhamar-Schuler et al. 2019). The NORA3 dataset with 3×3 km resolution (Haakenstad et al. 2020).	1958–2017 1998–2019
Precipitation	HD10	Sval-Imp: https://doi.org/10.11582/2018.00006 NORA3: Will become available at MET Norway	Norwegian Meteorological Institute	Ole Einar Tveito, MET	The Sval-Imp dataset with 1×1 km resolution based on ERA40 and ERA Interim (Østby et al. 2017, Vikhamar-Schuler et al. 2019). The NORA3 dataset with 3×3 km resolution (Haakenstad et al. 2020).	1958–2017 1998–2019
Permafrost monitoring	HD11	www.mosj.no/en/climate/land/permafrost.html	Norwegian Meteorological Institute	Ketil Isaksen, MET	Active layer thickness and permafrost temperature in the upper 15 m, Janssonhaugen, Adventdalen (Isaksen et al. 2001, Isaksen et al. 2007).	1999–2020
Snow cover	HD12	Sval-Imp: https://doi.org/10.11582/2018.00006 NORA3: Will become available at MET Norway	Norwegian Meteorological Institute	Ole Einar Tveito, MET	The Sval-Imp dataset with 1×1 km resolution based on ERA40 and ERA Interim (Østby et al. 2017, Vikhamar-Schuler et al. 2019). The NORA3 dataset with 3×3 km resolution (Haakenstad et al. 2020).	1958–2017 1998–2019

4. Estimation of indicators and rates of change

This section describes methods for how indicator values are calculated based on the datasets presented in section 3. First we describe the overall analytical framework used to estimate rates of change in abiotic indicators and indicators based on time-series (see Williams et al. 2021 for an example). Then we give brief presentations of the specific methods for each indicator, including methods used to estimate statistical uncertainties (Table 4.1a Low Arctic tundra and Table 4.1b High Arctic tundra). If assessment of uncertainties in that dataset was not possible, we have stated this in Table 4.1 a, b. Detailed appendices in Ch. 8 are important supplements to Ch. 4. They include graphical representations of all indicator values and background data for these values, as well as supplementary methods for estimating indicator values where required. All statistical analyses were conducted in R version 1.2.5042 (R Core Team 2020).

4.1 Abiotic indicators (climate) — estimation of rates of change after the reference period 1961–1990

To estimate linear rates of change, relative to the climatic reference period 1961–1990, a two-step bootstrap (i.e. a statistical method that resamples a dataset many times) has been used: 1) Non-parametric bootstrapping data for the first 30 years (1961–1990) as basis for estimating uncertainty around the mean for the reference period, 2) bootstrapping of data for all remaining years after the climatic reference period (1991–present) used to fit a linear regression model with the intercept given by the bootstrapped mean for the reference period.

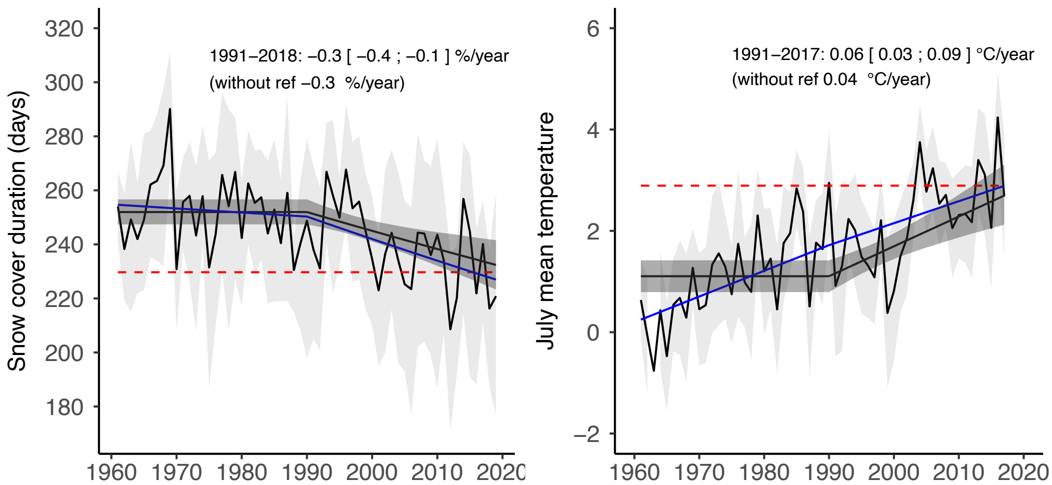


Figure 4.1. Example of how rates of change are estimated for the time-series for abiotic indicators (here illustrated by the indicators *Snow cover duration* for the Low Arctic and *July mean temperature* for the High Arctic). The black lines correspond to estimating the mean (without trend) in the reference period 1961–1990, followed by a trend for 1991–present (given here as a percentage as the model is fitted on a log-scale). The grey area is the 95 % confidence interval for the predicted mean value, and the dotted red line corresponds to the 95 % confidence limit for a single year (i.e. when the trend line for 1991–present crosses the dotted red line, it means that the average value of the indicator would have been considered as extreme in the reference period). The blue lines correspond to a segmented regression with trends in both the reference (1961–1990) and 1991–present periods (and with the latter rate of change expressed as "without ref." in the figure). When there is no trend before 1990 (Snow cover duration), using the "no-trend" model (black line) is adequate, but using the trends models for both periods should be preferred for July mean temperature (blue line).

We also fitted segmented models with trends in both the reference period and the most recent period (1991 onwards) in case changes started before 1990. However, not all abiotic indicators can be estimated based on linear relationships. For some indicators, which have linear rates of change on a log scale and Poisson distributions or a variance proportional to the mean (for instance counts such as the number of days), log-linear models were used, using quasi-likelihood methods in case of overdispersion. The difference between this approach and the default linear model is that the average for the reference period 1961–1990 was included as an offset in a generalised linear model (glm function). See Fig. 4.1 for details on how to interpret results.

4.2 Other indicators — estimation of rates of change in time-series

To estimate linear rates of change, regression models with different structure for the residuals were used. The best fitting model was chosen based on Akaike Information Criterion (AIC). The possible models included in the model selection were: 1) AR0, a standard linear regression with independent residuals, 2) AR1, a 1st order autoregressive model, 3) AR2, a 2nd order autoregressive model, 4) AR3, a 3rd order autoregressive model, 5) ARMA11, a 1st order autoregressive model with a 1st order moving average. Models were estimated using the function gls() in the nlme library (Pinheiro et al. 2020) in R. The predictions based on the best AIC selected model were calculated using the function predictSE.gls() in the AICmodavg library (Mazerolle 2020) in R. The REML method was used for the estimates, except in cases where the model failed to converge, in which case the ML method was used. In cases where the model was based on transformed data (log for counts or logit for proportions), back transformed predicted values are shown (see Fig. 4.2 for details). R^2 was calculated as the squared correlation between the predicted and the observed values, and 95 % confidence intervals of regression coefficients were estimated using the function intervals() in the nlme library (Pinheiro et al. 2020). For time series with a known AR-structure, for instance small rodent abundance, AR2-models were used by default (Bjørnstad et al. 1995, Henden et al. 2009). The best (AIC selected) model for each individual indicator is indicated on the figures of indicator values and background data shown in appendices 8.1.1 and 8.2.2. for Low and High Arctic indicators, respectively.

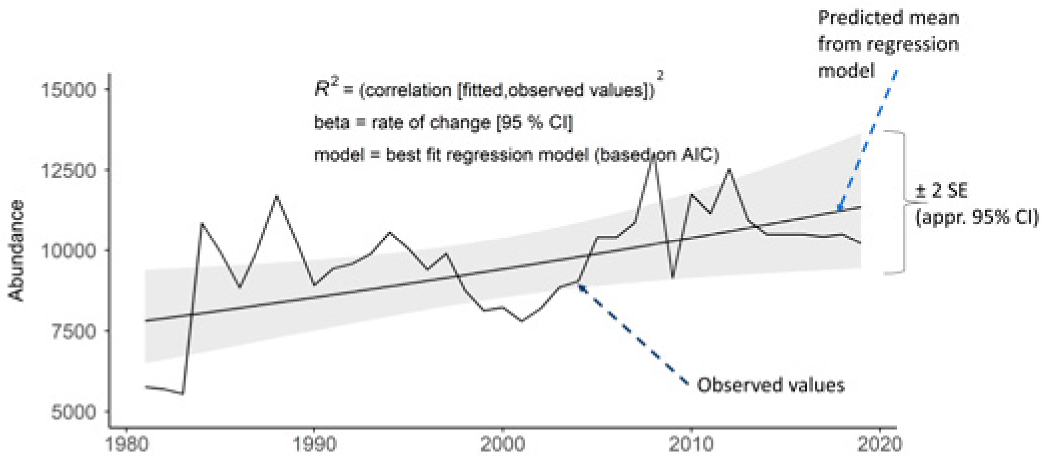


Figure 4.2. Generic example of how rates of change are described and estimated for the time-series for biotic indicators (here illustrated by the indicator Semi-domestic reindeer abundance). The rate of change, beta, is given with 95 % confidence intervals (CI). R^2 is the percentage of variance of the observed time-series explained by the fitted model. The structure of the best model is specified (e.g. AR2 for indicators with cyclic behaviour).

Table 4.1a. Methods for estimating indicators from the datasets for Low Arctic tundra. See also Table 3.2a and Appendix 8.1 for supplementary information.

Ecosystem characteristic	Indicator	Dataset ID	Methods
Primary productivity	Maximum vegetation productivity	LD01	Remotely sensed estimates are used (i.e. cover the whole ecosystem). Annual maximum productivity in the growing season is calculated as maximum EVI per pixel across all observed values in June–August each year. The indicator values are frequency distributions of the rate of change (regression coefficients) and a map that shows which areas have trends of greening or browning in the assessed time period. Rate of change in maximum vegetation productivity across all years is calculated per pixel with a linear regression (AR0) as described in 4.2.
Primary productivity	Start of growing season	LD01	Remotely sensed estimates are used (i.e. cover the whole ecosystem). The start of the growing season is calculated per pixel as the date where EVI is higher than 50 % of maximum vegetation productivity. The indicator values are frequency distribution of the rate of change (regression coefficients) and a map that shows which areas have earlier/later start of growing season. Rate of change in start of the growing season is calculated per pixel across all years with a linear regression (AR0) as described in 4.2.
Primary productivity	Plant biomass	LD02	The indicator value is annual standing biomass in meadow and heath. The rate of change is calculated per vegetation type with AR models as described in 4.2.
Biomass distribution among trophic levels	Plant growth forms versus rodents	LD02, LD04	Plant growth forms are represented by annual biomass of food and shelter related plant growth forms. Small rodents are represented by total abundance (capture/100 trap nights) of all small rodents per monitoring area and season (spring and autumn). The indicator value is the ratio between biomass of plant growth forms that offer food and shelter for rodents expressed as log ratio plant biomass:rodents. The rate of change is calculated per vegetation type with AR models as described in 4.2.
Biomass distribution among trophic levels	Plant growth forms versus ungulates	LD02, LD06	Plant growth forms are represented by annual standing biomass of palatable and unpalatable plant growth forms. Ungulates are represented by total abundance of reindeer on the level of herding district. The indicator value is the ratio between biomass of plant growth forms that are evaluated as palatable or unpalatable to ungulates expressed as log ratio plant biomass:reindeer. The rate of change is calculated with AR models as described in 4.2.
Biomass distribution among trophic levels	Rodents versus carnivorous vertebrates	LD06, LD10	Small rodents are represented by seasonal (spring and autumn) total abundance indexes (capture/100 trap nights) of all small rodents per monitoring area. Carnivorous vertebrates are long-tailed skua, rough-legged buzzard and snowy owl. They are represented by annual total abundance (number of breeding pairs) per monitoring area. The indicator value is the ratio between the two trophic levels expressed as log ratio small rodents:carnivores. The rate of change is calculated with AR models as described in 4.2.
Biomass distribution among trophic levels	Ungulates versus carnivorous vertebrates	LD06, LD09	Ungulates are represented by annual total abundance of reindeer in the herding districts on Varanger Peninsula. Carnivores are represented by red fox presence (annual proportion of days with red fox in camera traps). The indicator value is abundance ratio between the two trophic levels expressed as log ratio reindeer:red fox. The rate of change is calculated with AR models as described in 4.2.

Table 4.1a. Continued

Ecosystem characteristic	Indicator	Dataset ID	Methods
Functional groups within trophic levels	Plant growth forms	LD02	Plant growth forms are represented by annual standing biomass of the most abundant and/or functionally important species/species groups in meadow and heath, being forbs, palatable (silica-poor) grasses, silica-rich grasses and crowberry. Rates of change in plant biomass across all years is calculated per species/functional group and per vegetation type using AR models as described above. The indicator includes the biomass-ratio between these species/species groups expressed as log ratio.
Functional groups within trophic levels	Herbivorous vertebrates	LD04, LD06, LD07, LD11	Herbivorous vertebrates are represented by small rodents, willow ptarmigan, reindeer, and moose. Small rodents are represented by seasonal (spring and autumn) total abundance indices (capture/100 trap nights) of all rodents in the monitoring area. For willow ptarmigan annual estimated density on Varanger Peninsula as well as other areas in eastern Finnmark. Reindeer is represented by annual total abundance in each of the herding districts on Varanger Peninsula, while moose is represented by annual statistics for number of moose seen per hunting day in municipalities in eastern Finnmark with tundra habitats. The indicator values are: 1) Ratio between reindeer (more Arctic) and moose (more boreal) given as log ratio reindeer:moose, 2) abundance ratio between lemmings (more Arctic) and root vole/grey-sided vole (more boreal) expressed as log ratio lemming:vole, and 3) abundance ratio between willow ptarmigan and reindeer given as log ratio ptarmigan:reindeer. The rate of change is calculated with AR models as described in 4.2.
Functional groups within trophic levels	Carnivorous vertebrates	LD09, LD10	Carnivorous vertebrates are represented by annual presence of red fox, Arctic fox (proportion of days observed in camera traps), long-tailed skua and rough-legged buzzard. The indicator values are 1) ratio between Arctic fox (more Arctic) and red fox (more boreal) expressed as log ratio Arctic fox:red fox, and 2) abundance ratio between long-tailed skua (more Arctic) and rough-legged buzzard (more boreal) expressed as log ratio long-tailed skua: rough-legged buzzard. The rate of change is calculated with AR models as described in 4.2.
Functionally important species and biophysical structures	Thicket-forming willows	LD02	The indicator is represented by annual standing biomass of thicket-forming willows in primary vegetation types. The rate of change is calculated per vegetation type with AR models as described in 4.2.
Functionally important species and biophysical structures	Crowberry biomass	LD02	The indicator is represented by annual standing biomass of crowberry in primary vegetation types. The rate of change is calculated per vegetation type with AR models as described in 4.2.
Functionally important species and biophysical structures	Mountain birch in forest-tundra	LD15	The indicator is represented by density of live mountain birch (trees/m^2) as well as density of seedlings under 1.3 m height (plants/m^2) in permanent monitoring transects. The data do not allow calculation of rates of change.
Functionally important species and biophysical structures	Lemming abundance	LD05	The indicator value is annual, seasonal (spring, autumn) total abundance index (capture/100 trap nights) of lemmings per monitoring area. The rate of change is calculated with AR models as described in 4.2.

Table 4.1a. Continued

Ecosystem characteristic	Indicator	Dataset ID	Methods
Functionally important species and biophysical structures	Ptarmigan density	LD11, LD12	The indicator is represented by two different density indices; estimated number of ptarmigans in eastern Finnmark based on a population model (Henden et al. 2020) and annual probability for presence of ptarmigan estimated from pellet counts in permanent monitoring plots on Varanger Peninsula (Henden et al. 2011). The rate of change is calculated with AR models as described in 4.2.
Functionally important species and biophysical structures	Geometrid moth outbreaks	LD13, LD14	The indicator value is represented by an annual density estimate of geometrid moth larvae on mountain birch and willow. The estimates on birch are conducted by two methods: 1) the number of larvae found by one observer during a 10-minute search (1987–2018) and 2) the number of larvae detached by shaking 10 haphazardly collected 80 cm birch branches in a large plastic box (2018–present). Estimates on willow are the number of larvae detached by shaking 10 haphazardly collected 80 cm willow branches in a large plastic box (2019–present). The rate of change is calculated with a binomial generalised linear model.
Functionally important species and biophysical structures	Semi-domestic reindeer abundance	LD06	The indicator value is annual total abundance of reindeer in the herding districts that extend their summer pastures into Low Arctic tundra. The rate of change is calculated with AR models as described in 4.2.
Functionally important species and biophysical structures	Semi-domestic reindeer calf body mass	LD06	The indicator value is annual mean slaughter weight of reindeer calves in the herding districts that extend their summer pastures into Low Arctic tundra. The rate of change is calculated with AR models as described in 4.2.
Functionally important species and biophysical structures	Semi-domestic reindeer calf rate	LD06	The indicator value is the number of calves divided by the number of adult females in the herd the 31st March the same year in all herding districts that extend their summer pastures into Low Arctic tundra. Number of calves is measured as the number of calves the herder has marked with his/her individual earmark. The rate of change is calculated with AR models as described in 4.2.
Functionally important species and biophysical structures	Red fox camera index	LD09	The indicator value is the annual proportion of days with red foxes captured by camera traps in the management intervention and control areas. The rate of change in the indicator is calculated using AR models as described in 4.2.
Functionally important species and biophysical structures	Large predators	LD18	Large predator abundance is represented by the abundance of the two large predator species expected in intact low Arctic tundra ecosystems, the wolverines and the wolf. The indicator value for wolverine is the number of successful wolverine reproductions in Finnmark, while the indicator for wolves is the number of resident wolves in Finnmark. The abundance of wolves has shown no change, being zero throughout the data temporal coverage period. The rate of change in the indicator for wolverine abundance is calculated using AR models as described in 4.2.
Landscape-ecological patterns	Snowbed encroachment	LD03	The indicator value is the annual proportion of permanent monitoring plots in snowbeds that have presence of dwarf shrubs. The rate of change in the indicator is calculated using AR models as described in 4.2.
Landscape-ecological patterns	Bioclimatic subzones	LD16, LD17	The indicator value is the total tundra area that is climatically within the bioclimatic subzones D (or colder), subzone E and subzone F (the northern boreal zone) calculated for the climatic reference period (1961–1990) and for each 10-year period thereafter. Rates of change are not calculated.

Table 4.1a. Continued

Ecosystem characteristic	Indicator	Dataset ID	Methods
Landscape-ecological patterns	Wilderness areas	LD16	The indicator value is the total area unaffected by major technical infrastructure calculated for each bio-climatic subzone for each status year (1988, 1998, 2003, 2008, 2013). The data do not allow calculation of rates of change.
Biological diversity	Plant communities	LD02	Heath and meadow plant communities are represented as their average number and abundance of plant species. The change in the indicator is demonstrated using box plots from data sampled in two distinct periods, 2005 to 2008 and 2019 to 2020. The data do not allow calculation of change rates.
Biological diversity	Arctic fox abundance	LD08	The indicator value is the annual number of litters observed in the management intervention and control areas, respectively. The rate of change in the indicator is calculated using AR models as described in 4.2.
Biological diversity	Arctic fox litter size	LD08	The indicator value is the annual litter size observed at dens in the management intervention and control areas, respectively. The rate of change in the indicator is calculated using AR models as described in 4.2.
Biological diversity	Arctic fox camera index	LD09	The indicator value is the proportion of days with Arctic foxes captured by camera traps in the management intervention and control areas. The rate of change in the indicator is calculated using AR models as described in 4.2.
Biological diversity	Snowy owl abundance	LD10	The indicator value is the annual number of nesting pairs of snowy owl in permanent monitoring areas. The data do not allow calculation of change rates.
Biological diversity	Snowy owl fecundity	LD10	The indicator value is the annual litter size of nesting pairs of snowy owl in permanent monitoring areas. The data do not allow calculation of change rates.
Biological diversity	Bird communities	LD17	Bird communities are represented by the total estimated abundance of bird species divided into habitat preference (open versus shrub tundra species). The indicator value is the ratio between open tundra and shrub associated species expressed as log ratio tundra species:shrub species. In addition, species richness of tundra species is used as an indicator of species diversity. Abundance and species richness are estimated from occupancy/N-mixture models. The rate of change in the indicators are calculated using AR models as described in 4.2.
Abiotic factors	Days with extreme cold	LD19	The indicator value is the annual number of days during the winter season (Nov.–Apr.) that have an average temperature < - 30°C for tundra and ecotone. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (here 1991–present) is shown. The rates of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	Winter melt days	LD19	The indicator value is the annual number of days during the winter season (Nov.–Apr.) that have an average temperature above 0°C for tundra and ecotone. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (1991–present) is shown. The rate of change in the indicator is calculated using log-linear models as described in 4.1.

Table 4.1a. Continued

Ecosystem characteristic	Indicator	Dataset ID	Methods
Abiotic factors	Degree days	LD19	The indicator value is the total number of days in a year with a daily mean > 5°C. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (here 1991–present) is shown. The rate of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	Growing degree days	LD19	The indicator value is the sum of temperatures > 5°C during the growing season (May–Oct.) for tundra and ecotone. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (here 1991–present) is shown. The rate of change in the indicator is calculated using log-linear models as described for abiotic indicators in 4.1.
Abiotic factors	Annual mean temperature	LD19	The indicator is the yearly average of daily mean air temperature. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (here 1991–present) is shown. The rate of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	January mean temperature	LD19	The indicator is the yearly average of daily mean temperatures in January. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (here 1991–present) is shown. The rate of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	July mean temperature	LD19	The indicator is the yearly average of daily mean temperatures in July. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (here 1991–present) is shown. The rate of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	Annual precipitation	LD20	The indicator value is the annual accumulated precipitation within the tundra and ecotone. In addition, the distribution of pixel-based rates of change over all years after the climatic reference period (i.e. 1991–present) is used. The rate of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	Precipitation during growing season	LD20	The indicator value is the annual accumulated precipitation during the growing season (May–Oct.) for tundra and ecotone. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (1991–present) is used. The rate of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	Snow cover duration	LD21	The indicator value is the annual number of days with snow cover during the winter season (Nov.–Apr.) for tundra and ecotone. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (1991–present) is used. The rate of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	Basal ice	LD22	The indicator value is the annual proportion of snow profiles that have hard snow or ice in the lowest 5 cm close to the ground. The rate of change in the indicator is calculated using log-linear models as described in 4.1.

Table 4.1b. Methods for estimating indicators from the datasets for High Arctic tundra. See also Table 3.2b and Appendix 8.2 for supplementary information.

Ecosystem characteristic	Indicator	Dataset ID	Methods
Primary productivity	Maximum vegetation productivity	HD01	Remotely sensed estimates are used (i.e. cover the whole ecosystem). Annual maximum productivity in the growing season is calculated as maximum EVI per pixel across all observed values in June–August each year. Rate of change in maximum vegetation productivity across all years is calculated per pixel with a linear regression (AR0). The indicator values are frequency distributions of the rate of change (regression coefficients) and a map that shows which areas have trends of greening or browning in assessed time period. Rate of change in maximum vegetation productivity across all years is calculated per pixel with a linear regression (AR0) as described in 4.2.
Primary productivity	Start of growing season	HD01	Remotely sensed estimates are used (i.e. cover the whole ecosystem). The start of the growing season is calculated per pixel as the date where EVI is higher than 50 % of maximum vegetation productivity. Rate of change in start of the growing season is calculated per pixel across all years with a linear regression (AR0). The indicator values are frequency distribution of the rate of change (regression coefficients) and a map that shows which areas have earlier/later start of growing season. Rate of change in start of the growing season across all years is calculated per pixel with a linear regression (AR0) as described in 4.2.
Biomass distribution among trophic levels	Maximum vegetation productivity versus Svalbard reindeer	HD01, HD02	In the absence of time series on the biomass of plant growth forms, the same data as for the indicator *Maximum vegetation productivity* (i.e. proxy for plant biomass), are used. Average maximum productivity is calculated for the census areas for reindeer in Adventdalen and Brøggerhalvøya, respectively. The Svalbard reindeer is represented by the total number of reindeer within the census areas. The indicator value is the ratio between the two trophic levels expressed as log ratio maximum vegetation productivity:Svalbard reindeer. The rate of change in the indicator is calculated with AR-models as described in 4.2.
Biomass distribution among trophic levels	Maximum vegetation productivity versus geese	HD01, HD04, HD05	In the absence of time series on the biomass of plant growth forms, the same data as for the indicator *Maximum vegetation productivity* (i.e. proxy for plant biomass), are used. Average maximum productivity is calculated for Nordenskiöld Land. Geese are represented by the overall annual population estimates for barnacle geese and pink-footed geese based on counts in the non-breeding season (winter and spring staging areas). The indicator values is the ratio between the two trophic levels expressed as log ratio maximum vegetation productivity:geese. The rate of change in the indicator is calculated with AR-models as described in 4.2.
Biomass distribution among trophic levels	Herbivorous vertebrates versus Arctic fox	HD02, HD04, HD05, HD06	Herbivore vertebrates consists here of pink-footed goose, barnacle goose, and Svalbard reindeer. Geese are represented by the overall annual population estimates for barnacle goose (based on total counts in wintering areas) and pink-footed goose (based on an integrated population model of median spring population abundance (Johnson et al. 2020). The Svalbard reindeer is represented by the total number of reindeer within the census areas in Adventdalen and Brøggerhalvøya. Arctic foxes are represented by the annual proportion of known breeding dens that are in use within the monitoring areas for the Arctic fox. The indicator values are the ratio between the two trophic levels expressed separately for geese and Svalbard reindeer as resp log ratio geese:Arctic fox and log ratio Svalbard reindeer:Arctic fox. The rate of change in the indicator is calculated with AR-models as described in 4.2.

Table 4.1b. Continued

Ecosystem characteristic	Indicator	Dataset ID	Methods
Functional groups within trophic levels	Herbivorous vertebrates	HD02, HD04, HD05, HD07	Herbivore vertebrates consists here of pink-footed goose, barnacle goose, Svalbard rock ptarmigan, and Svalbard reindeer. Svalbard rock ptarmigan is represented by estimates of annual density of territorial males (density/km^2) based on point transect sampling surveys. Geese are represented by the overall annual population estimates for barnacle goose (based on total counts in wintering areas) and pink-footed goose (based on an integrated population model of median spring population abundance). The Svalbard reindeer is represented by the total number of reindeer within the census areas. The ratio between Svalbard rock ptarmigan and geese is expressed by log ratio Svalbard rock ptarmigan:geese. The rate of change in the indicator is calculated with AR-models as described in 4.2.
Functionally important species and biophysical structures	Pink-footed goose abundance	HD04	The indicator value is the estimated annual median population number from spring staging areas based on an integrated population model. The rate of change in the indicator is calculated with AR-models as described in 4.2.
Functionally important species and biophysical structures	Barnacle goose abundance	HD05	The indicator value is the annual total number of barnacle goose populations from census in the winter-ing areas. The rate of change in the indicator is calculated with AR-models as described in 4.2.
Functionally important species and biophysical structures	Svalbard reindeer abundance	HD02	The indicator value is the annual total abundance of Svalbard reindeer in Adventdalen, Brøggerhalvøya and Reindalen, respectively. The rate of change in the indicator is calculated with AR-models as described in 4.2.
Functionally important species and biophysical structures	Svalbard reindeer mortality rate	HD03	The indicator value is the annual total number of Svalbard reindeer carcasses in the census area Adventdalen. The rate of change in the indicator is calculated with AR-models as described in 4.2.
Functionally important species and biophysical structures	Svalbard reindeer calf rate	HD02	The indicator value is the annual number of calves per female in the census area of Adventdalen. The rate of change in the indicator is calculated with AR-models as described in 4.2.
Functionally important species and biophysical structures	Arctic fox abundance	HD06	The indicator value is the annual proportion of known breeding dens that are in use in the monitoring areas for the Arctic fox (Adventdalen/Sassendalen and Brøggerhalvøya/Kongsfjorden). The rate of change in the indicator is calculated with AR-models as described in 4.2.
Landscape-ecological patterns	Bioclimatic subzones	HD09, HD10	The indicator value is the overall tundra area that climatically is located within the bioclimatic subzones A, B and C calculated for the climatic reference period (1961–1990) and for each 10-year period after this. The rate of changes is not calculated.
Landscape-ecological patterns	Wilderness areas	HD08	The indicator value is the overall area without major infrastructure in each bioclimatic subzone for each status year (1990, 2015, 2019). The data do not allow calculations of rate of change.
Biological diversity	Svalbard rock ptarmigan breeding abundance	HD07	The indicator value is the annual density of territorial males (density/km2) based on point transect sam-pling surveys in the monitoring area. The rate of change in the indicator is calculated with AR-models as described in 4.2.

Table 4.1b. Continued

Ecosystem characteristic	Indicator	Dataset ID	Methods
Abiotic factors	Days with extreme cold	HD09	The indicator value is the annual number of days during the winter season (Nov.– Apr.) that have an average temperature < –30°C for tundra and ecotone. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (1991–present) is shown. The rate of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	Winter melt days	HD09	The indicator value is the annual number of days during the winter season (Nov.– Apr.) that have an average temperature above 0°C for tundra and ecotone. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (1991–present) is shown. The rate of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	Degree days	HD09	The indicator value is the total number of days in a year with a daily mean > 5°C. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (here 1991–present) is shown. The rate of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	Growing degree days	HD09	The indicator value is the sum of temperatures > 5°C during the growing season (May–Oct.) for tundra and ecotone. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (here 1991–present) is shown. The rate of change in the indicator is calculated using log-linear models as described for abiotic indicators in 4.1.
Abiotic factors	Annual mean temperature	HD09	The indicator is the yearly average of daily mean air temperature. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (1991–present) is shown. The rate of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	July mean temperature	HD09	The indicator is the yearly average of daily mean air temperature in July. In addition, the distribution of pixel-based change rates over all years after the climatic reference period (1991–present) is shown. The rate of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	Annual precipitation	HD10	The indicator value is the annual accumulated precipitation within the tundra and ecotone. In addition, the distribution of pixel-based rates of change over all years after the climatic reference period (1991–present) is used. The rate of change in the indicator is calculated using log-linear models as described in 4.1.
Abiotic factors	Permafrost	HD11	The indicator value is annual permafrost temperature on 5, 10 and 15 m depth, and annual maximum depth of the active layer. The rate of change in the indicator is calculated with AR-models as described 4.2.
Abiotic factors	Snow cover duration	HD12	The indicator value is annual number of days during winter (Nov.– Apr.) with snow cover. In addition, the distribution of pixelwise rate of changes over all years after the climatic reference period (here 1991–2017) are used. The rate of change in the indicator are calculated with linear models as described for abiotic indicators in 4.1.

5. Assessment of deviations from the reference condition

This section describes the methods used to assess deviation from the reference condition and the scientific evidence base for the phenomena. In Table 5.1, we list which phenomena are linked to each individual indicator, and the general approach used to assess whether, and to what degree, these phenomena have occurred (Table 5.1a Low Arctic tundra; Table 5.1b High Arctic tundra). The three approaches are, as described in the protocol by Jepsen et al. (2020):

- **Method 1) — quantitative phenomena**
  The values of the indicator relative to an estimated quantitative threshold value.
- **Method 2) — qualitative phenomena**
  The value of the indicator relative to variation estimated from the indicator time series (the type and direction of rates of change) or other qualitative or quantitative information about a reference condition.
- **Method 3) — all phenomena**
  Observed and expected effects of changes in the indicator on other components of the ecosystem (i.e. ecosystem significance).

The PAEC of Arctic tundra is based on analyses of 34 datasets supporting 26 indicators unique to Low Arctic tundra and eight indicators unique to High Arctic tundra ecosystems as well as 16 shared indicators. Most indicators are derived from the ecosystem-based Climate-ecological Observatory of Arctic Tundra (COAT) and Environmental Monitoring of Svalbard and Jan Mayen (MOSJ), dedicated specifically to the monitoring of Norwegian Arctic tundra ecosystems. Photos: E. Soininen/UiT (upper left), T. Nordstad/NPI (lower left), B. Frantzen/NIBIO (middle), R.A.Ims/UiT (upper right), Ø. Overrein/NPI (lower right)

Table 5.1a. List of phenomena including approaches (see above) used to determine the extent to which each phenomenon has occurred in Low Arctic tundra. Approach refers to methods used to determine the extent to which the phenomenon has occurred.

Indicator [ID]	Phenomenon [ID]	Anthropogenic drivers	Approach
Maximum vegetation productivity [LI01]	Changes in maximum productivity — greening and browning [LP01]	Climate change	2) and 3)
Start of growing season [LI02]	Earlier start of the growing season [LP02]	Climate change	2) and 3)
Plant biomass [LI03]	Changes in standing plant biomass [LP03]	Climate change, grazing	2) and 3)
Plant growth forms versus rodents [LI04]	Increased plant biomass in relation to rodents in the food web [LP04]	Climate change, grazing	2) and 3)
Plant growth forms versus ungulates [LI05]	Changes in the relative biomass of plant growth forms and ungulates [LP05]	Climate change, grazing, natural resource management	2) and 3)
Rodents versus carnivorous vertebrates [LI06]	Decreasing biomass of carnivorous vertebrates relative to rodents [LP06]	Climate change, natural resource management	2) and 3)
Ungulates versus carnivorous vertebrates [LI07]	Changes in the relative biomass of ungulates and carnivorous vertebrates [LP07]	Climate change, natural resource management	2) and 3)
Plant growth forms [LI08]	Changes in the composition of plant growth forms in the plant community [LP08]	Climate change, grazing	2) and 3)
Herbivorous vertebrates [LI09]	Changes in the composition of functional groups within the herbivore vertebrate community [LP09]	Climate change, harvest, natural resource management	2) and 3)
Carnivorous vertebrates [LI10]	Borealisation of the carnivorous vertebrate community [LP10]	Climate change, natural resource management	2) and 3)
Thicket-forming willows [LI11]	Changes in abundance of thicket-forming willows in river valleys [LP11]	Climate change, grazing	2) and 3)
Crowberry biomass [LI12]	Increased abundance of crowberry in open vegetation types [LP12]	Climate change	2) and 3)
Mountain birch in forest-tundra [LI13]	1) Weakened recruitment after moth outbreaks [LP13] and 2) Sustained reduction of forested area and/or forest density [LP14]	Climate change, grazing	2) and 3)
Lemming abundance [LI14]	Less frequent, less distinct peaks in the lemming cycle [LP15]	Climate change	2) and 3)
Ptarmigan density [LI15]	Low and/or decreasing abundance of willow ptarmigan [LP16]	Climate change, hunting	2) and 3)
Geometrid moth outbreaks [LI16]	1) Invasion of new moth species that establish as outbreak species in the forest-tundra ecotone [LP17] and 2) Establishment and spread of new moth species in willow shrub tundra far from birch forest [LP18].	Climate change	2) and 3)
Semi-domestic reindeer abundance [LI17]	Change in abundance of semi-domestic reindeer [LP19]	Climate change, natural resource management	2) and 3)
Semi-domestic reindeer calf body mass [LI18]	Low or decreasing semi-domestic reindeer calf body mass [LP20]	Climate change, natural resource management	2) and 3)
Semi-domestic reindeer calf rate [LI19]	Low or decreasing semi-domestic reindeer calf rate [LP21]	Climate change, natural resource management	2) and 3)
Red fox camera index [LI20]	Increased or high proportion of days with red fox captures by camera traps [LP22]	Climate change, hunting, natural resource management	2) and 3)

Table 5.1a. Continued

Indicator [ID]	Phenomenon [ID]	Anthropogenic drivers	Approach
Large predators [LI21]	Low abundance of wolverines and wolves in Low Arctic tundra [LP23]	Natural resource management, hunting	2) and 3)
Snowbed encroachment [LI22]	Increasing presence or cover of woody plants in snowbeds [LP24]	Climate change, grazing	2) and 3)
Bioclimatic subzones [LI23]	Decreasing total area that meets climate criteria for Low Arctic tundra zones D and E [LP25]	Climate change	1), 2) and 3)
Wilderness areas [LI24]	Decreasing total area of wilderness areas [LP26]	Infrastructure development	2) and 3)
Plant communities [LI25]	Increased proportion of boreal or woody species at the expense of Arctic or herbaceous species [LP27]	Climate change	2) and 3)
Arctic fox abundance [LI26]	Absence of sustained increase in Arctic fox population despite conservation efforts [LP28]	Climate change, natural resource management	2) and 3)
Arctic fox litter size [LI27]	Small or decreasing litter size of Arctic fox [LP29]	Climate change, natural resource management	2) and 3)
Arctic fox camera index [LI28]	Absence of sustained increase in the proportion of days with Arctic fox captures by camera traps despite conservation efforts [LP30]	Climate change, natural resource management	2) and 3)
Snowy owl abundance [LI29]	Absence of breeding snowy owls during the majority of peak rodent years linked to low lemming abundance [LP31]	Climate change	2) and 3)
Snowy owl fecundity [LI30]	Low and/or decreasing snowy owl clutch size during peak rodent years [LP32]	Climate change	2) and 3)
Bird communities [LI31]	Decreasing abundance and species diversity among open tundra species [LP33]	Climate change	2) and 3)
Days with extreme cold [LI32]	Decreasing frequency of days with extreme cold [LP34]	Climate change	2) and 3)
Winter melt days [LI33]	Increasing frequency of winter melt days [LP35]	Climate change	2) and 3)
Degree days [LI34]	Increasing number of degree days [LP36]	Climate change	2) and 3)
Growing degree days [LI35]	Increasing growing degree day sum during the growing season [LP37]	Climate change	2) and 3)
Annual mean temperature [LI36]	Increasing annual temperature [LP38]	Climate change	2) and 3)
January mean temperature [LI37]	Increasing January temperature [LP39]	Climate change	2) and 3)
July mean temperature [LI38]	Increasing July temperature [LP40]	Climate change	2) and 3)
Annual precipitation [LI39]	Changes in annual precipitation [LP41]	Climate change	2) and 3)
Precipitation during growing season [LI40]	Changes in precipitation during the growing season [LP42]	Climate change	2) and 3)
Snow cover duration [LI41]	Shorter season with snow cover [LP43]	Climate change	2) and 3)
Basal ice [LI42]	Increasing presence of basal ice/hard snow in the bottom layer [LP44]	Climate change	2) and 3)

Table 5.1b. List of phenomena including approaches (see above) used to determine the extent to which each phenomenon has occurred in High Arctic tundra. Approach refers to methods used to determine the extent to which the phenomenon has occurred.

Indicator [ID]	Phenomenon [ID]	Anthropogenic drivers	Approach
Maximum vegetation productivity [HI01]	Changes in maximum vegetation productivity — greening and browning [HP01]	Climate change	2) and 3)
Start of growing season [HI02]	Earlier start of growing season [HP02]	Climate change	2) and 3)
Maximum vegetation productivity versus Svalbard reindeer [HI03]	Changes in the ratio of maximum vegetation productivity to Svalbard reindeer abundance [HP03]	Climate change	2) and 3)
Maximum vegetation productivity versus geese [HI04]	Increased geese biomass relative to maximum vegetation productivity [HP04]	Climate change, hunting	2) and 3)
Herbivorous vertebrates versus Arctic fox [HI05]	Changes in relative biomass of herbivorous vertebrates and Arctic fox [HP05]	Climate change, hunting	2) and 3)
Herbivorous vertebrates [HI06]	Changes in composition of the functional group herbivorous vertebrates [HP06]	Climate change, hunting, resource management	2) and 3)
Pink-footed goose abundance [HI07]	Changes in the abundance of pink-footed geese [HP07]	Hunting, climate change, farmland policy	2) and 3)
Barnacle goose abundance [HI08]	Changes in the abundance of barnacle geese [HP08]	Climate change, farmland policy	2) and 3)
Svalbard reindeer abundance [HI09]	Decrease in the abundance of Svalbard reindeer [HP09]	Climate change, hunting	2) and 3)
Svalbard reindeer mortality rate [HI10]	High or increasing mortality rate of Svalbard reindeer [HP10]	Climate change, hunting	2) and 3)
Svalbard reindeer calf rate [HI11]	Low or decreasing calf rate of Svalbard reindeer [HP11]	Climate change, hunting	2) and 3)
Arctic fox abundance [HI12]	Decreasing abundance of Arctic fox [HP12]	Climate change, trapping	2) and 3)
Bioclimatic subzones [HI13]	Decreasing total area that meets climate criteria for the High Arctic tundra zones A, B, and C [HP13]	Climate change	1), 2) and 3)
Wilderness areas [HI14]	Decreasing total area of wilderness areas [HP14]	Infrastructure development	2) and 3)
Svalbard rock ptarmigan breeding abundance [HI15]	Decreasing abundance of breeding Svalbard rock ptarmigan [HP15]	Climate change, hunting	2) and 3)
Days with extreme cold [HI16]	Decreasing frequency of days with extreme cold [HP16]	Climate change	2) and 3)
Winter melt days [HI17]	Increasing frequency of winter melt days [HP17]	Climate change	2) and 3)
Degree days [HI18]	Increasing number of degree days [HP18]	Climate change	2) and 3)
Growing degree days [HI19]	Increasing growing degree day sum during the growing season [HP19]	Climate change	2) and 3)
Annual mean temperature [HI20]	Increasing annual mean temperature [HP20]	Climate change	2) and 3)

Table 5.1b. Continued

Indicator [ID]	Phenomenon [ID]	Anthropogenic drivers	Approach
July mean temperature [HI21]	Increasing July temperature [HP21]	Climate change	2) and 3)
Annual precipitation [HI22]	Changes in annual precipitation [HP22]	Climate change	2) and 3)
Permafrost [HI23]	Increasing temperature in the top 15 m of permafrost [HP23] and 2) Increased thickness of the active layer [HP24]	Climate change	2) and 3)
Snow cover duration [HI24]	Shorter snow season [HP25]	Climate change	2) and 3)

Climate change is the main anthropogenic driver of Svalbard reindeer populations, while hunting has only limited impact. Photo: R. Eidesen

5.1 Scientific evidence base for the phenomena

5.1.1 Scientific evidence base — Low Arctic tundra

Indicator: Maximum vegetation productivity [LI01]

Phenomenon: Changes in maximum productivity — greening and browning [LP01]

Ecosystem characteristic: Primary productivity

Under the reference condition, maximum primary production (maximum growth of biomass per unit of area in growing season) defined for the Low Arctic bioclimatic subzones D and E (CAVM Team 2003, Raynolds et al. 2012) is mainly limited by temperature during the growing season (Elmendorf et al. 2012). Within these subzones, the indicator will vary between different types of vegetation and landscape, for example owing to topographic, edaphic, and hydrological conditions. Data from field-based or remote sensing studies, on which to base reference values, are unavailable for Norwegian Low Arctic regions during the climatic reference period. However, consistent change rates in indicators monitored by remote sensing, when interpreted in relation to changes in important drivers, provide good indicators of change and are widely used across the Arctic for monitoring regional scale processes (Frey et al. 2020).

The most important anthropogenic drivers of change in this indicator are climate change (i.e. changed growing conditions; Beck and Goetz 2011, Vickers et al. 2016) and grazing (i.e. managed herbivores; Bråthen et al. 2017). Climate change can also affect the indicator indirectly through intensification of insect outbreaks (Jepsen et al. 2009a, Jepsen et al. 2009b), particularly in the ecotone, or through reduced grazing pressure from rodents (Olofsson et al. 2012) owing to absence or suppression of cyclic peak years (Ims et al. 2011, Kleiven et al. 2018). The links to anthropogenic drivers (climatic and biotic) are assessed as <u>certain</u>, but plant biomass and maximum vegetation productivity are often complex results of multiple drivers operating on different scales, making it a challenge to distinguish the effects of different drivers. The understanding of the importance of changes in plant productivity in the Low Arctic ecosystem is assessed as <u>good</u>. Plant productivity influences the availability of forage for large and small herbivores, with implications for body mass and reproductive success of ungulates, for example (Hamel et al. 2011, Henden et al. 2021b, Tveraa et al. 2013). The phenomenon must be assessed in different ways for tundra and ecotone, and both greening and browning trends can indicate worsened condition, depending on the cause. In tundra, greening trends indicate that the system is shifting towards a more productive, and hence less Arctic condition. Greening trends can be considered of **ecosystem significance** if, for example, i) increased productivity can be linked to increases in thickets, ii) productivity over time in tundra areas approaches or corresponds to that of forest or tall shrub areas of the ecotone. Browning trends in the tundra may indicate vegetation damage during winter and can be considered of **ecosystem significance** if, for example, i) they can be linked to detrimental weather events and are extensive enough to affect the availability of forage for grazers. In the ecotone, browning trends indicate effects of either climatic (drought) or biotic (insect outbreaks) drivers. Browning trends in the ecotone can be considered of **ecosystem significance** if, for example, i) they affect the land use patterns of grazers or game animals, ii) they last considerably longer than the immediate effect, thus involving forest mortality and/or prolonged lack of regeneration of the vegetation.

Indicator: Start of growing season [LI02]

Phenomenon: Earlier start of the growing season [LP02]

Ecosystem characteristic: Primary productivity

Under the reference condition, the start of the growing season (i.e. spring green-up of vegetation), is in principle determined by the climate regime during the reference period 1961–1990. Although data on climate are available from that period, the climate variables of interest lack the spatial resolution required to define snow conditions and temperatures relevant for vegetation and thus also to set reference values for the Norwegian Low Arctic.

The most important anthropogenic driver of changes in this condition is climate change. Start of the growing season is affected by temperature and snowmelt, and changes in climate are expected to lead to earlier start of the growing season in tundra and ecotone owing to earlier snowmelt and higher spring temperatures. The links to these drivers are assessed as certain (Iler et al. 2017). The timing of the start of the growing season is crucial to many trophic interactions (Durant et al. 2005, Høye et al. 2007) and, like the indicator *Maximum vegetation productivity*, influences body mass and reproductive success of ungulates, for example. This effect can be either positive (Tveraa et al. 2013) or negative (Kerby and Post 2013) depending on the underlying mechanism of action. The understanding of changes in this phenomenon is thus assessed as good. Changes in the start of the growing season can be considered of **ecosystem significance** if, for example, i) they result in increased mismatch between the timing of the start of the growing season and the timing of reindeer calving, ii) they drive extensive changes in vegetation by lengthening the growing season/ snow free season, iii) they result in increased match between the timing of moth larvae hatching and birch bud burst.

Indicator: Plant biomass [LI03]

Phenomenon: Changes in standing biomass [LP03]

Ecosystem characteristic: Primary productivity

Under the reference condition, standing biomass of vascular plants in the Low Arctic bioclimatic subzones D and E consists of herbaceous and woody plants, with woody plants being prostrate, dwarf or low-statured shrubs (Walker et al. 2012). Climate, being highly variable in temperature and precipitation within and among growing seasons, causes variation in the onset of the growing season as well as variation in the conditions for growth during the growing seasons (Walker et al., 2012). Furthermore, within the subzones of the Low Arctic, standing biomass will vary considerably between different types of landscape due to topographic, edaphic, and hydrological conditions (Walker et al. 2012). Finally, standing biomass will vary due to interactions with herbivores (Ims and Fuglei 2005) and the type of growth forms making up the vegetation (Bråthen et al. 2018). For instance, plant biomass values from 2006 to 2008 in the Low Arctic confirms that standing biomass is highly variable between years and with herbivory (Ravolainen et al. 2011). Furthermore, regional estimates of plant biomass from the low alpine zone of northern Fennoscandia in 2003 (Bråthen and Lortie 2016), being comparable to that of the Low Arctic (Killengreen et al. 2007), confirm the production of standing biomass to be highly variable, spanning estimates from close to zero up to 800 grams per square meter. Importantly, standing biomass is related to vascular plant species richness (Bråthen and Lortie 2016), with changes in biomass likely to have consequences for ecosystem functionality. Consistent rates of change in standing biomass of important types of vegetation in the ecosystem (reflecting changes in net primary production) can be interpreted in relation to changes in important drivers, providing good indicators of deviation from a good condition.

The most important anthropogenic driver of change in this indicator is climate change, through alteration of growing conditions (Beck and Goetz 2011, Bråthen et al. 2018, Vickers et al. 2016), and grazing by large herbivores (Bråthen et al. 2017). An important natural driver is grazing by rodents (Olofsson et al. 2014), which can also be linked to anthropogenic climate change through suppression or elimination of cyclic population peaks (Cornulier et al. 2013). The links to anthropogenic drivers (climatic and biotic) are assessed as certain (van der Wal and Stien 2014), but as indicated above, plant biomass is the result of multiple drivers operating on different scales, making it a challenge to distinguish the effects of different drivers. As for the indicator *Maximum vegetation productivity*, the understanding of the role of this indicator in Low Arctic ecosystems is assessed as good. Reduced plant biomass indicates deteriorating growing conditions and/or that an increasing proportion of the primary production is grazed or trampled. A major increase in plant biomass indicates changes towards a less Arctic system. Changes can be considered of **ecosystem significance** if, for example, i) increased biomass can be linked to a decrease in the overall species richness, ii) increased biomass can be linked to a decrease in the abundance of the most species rich growth forms such as forbs.

Climate change causes both greening and browning of Arctic vegetation and can be linked to changes in plant community composition and interactions between plants and herbivores. Upper panel: Where crowberry establishes, whose leaves are non-palatable to herbivores and toxic to seedlings, the establishment and growth of other more fast-growing plants is hindered, in turn reducing primary production. Silica-rich grasses have high primary production and biomass production, but this biomass is hardly grazed and hence they have little importance as food in trophic interactions. Lower panel: A defoliated twig under an outbreak of the winter moth, which is a boreal/nemoral species that has caused reduced primary productivity (browning) in the forest-tundra ecotone and the Low Arctic shrub-tundra. Photos: K.A. Bråthen/UiT (upper left, upper right), O.P. Vindstad/UiT (lower left), J. Iglhaut/NINA (lower right).

Indicator: Plant growth forms versus rodents [LI04]
Phenomenon: Increased plant biomass in relation to rodents in the food web [LP04]
Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, rodents (tundra vole, grey-sided vole, and Norwegian lemming) and associated plant growth forms show synchronised, 4 to 5-year biomass cycles with a regularity and amplitude that help maintain characteristic Low Arctic tundra vegetation types, such as snowbeds and meadows (Nystuen et al. 2014, Ravolainen et al. 2014).

The most important anthropogenic drivers of change in this indicator are climate change (Myers-Smith et al. 2015) and grazing by large herbivores (Bråthen et al. 2007, Bråthen et al. 2017, Ravolainen et al. 2011). The links to these drivers are assessed as certain. Climate change alters growing conditions for different plant growth forms differently (Elmendorf et al. 2012), and affects rodent population cycles (Berteaux et al. 2017, Kausrud et al. 2008). Grazing by managed herbivores and activities by the small rodents themselves influence plant growth forms differently (Bråthen et al. 2017, Ravolainen et al. 2011, Tuomi et al. 2019). Different rodent species use different plant growth forms as food and/or shelter, and the strength of these relationships varies between rodent peaks (Soininen et al. 2018). Higher temperatures are expected to increase the biomass of woody plants more than herbaceous plant groups (Christie et al. 2015, Elmendorf et al. 2012). This will reduce forage quality but increase shelter availability. Thus, higher temperatures are expected to shift biomass towards more shelter plant biomass relative to rodent biomass. Increased grazing by large herbivores can also contribute to increased shelter, as grazing increases the abundance of silica-rich tussock-forming grasses (Ravolainen et al. 2011, Soininen et al. 2018). The expected changes for the ratio between food plant biomass and rodent biomass are less clear. Greater irregularity and/or suppression of rodent population cycles in a warmer Arctic weakens the effect of grazing pulses on the vegetation and thus perturbs the correlated dynamics between herbivores and plants in this food web (Olofsson et al. 2014, Ravolainen et al. 2014). The understanding of the significance of these changes is assessed as less good.

Changes in the biomass ratio between plants and rodents can be considered of **ecosystem significance** if, for example, i) the shift is caused by increase of woody shelter plants in open vegetation types.

Indicator: Plant growth forms versus ungulates [LI05]
Phenomenon: Changes in the relative biomass of plant growth forms and ungulates [LP05]
Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, ungulate population size and grazing pressure contribute to maintaining grazed plant growth forms in a state characteristic of Low Arctic tundra (subzones D and E).

The most important anthropogenic drivers of change in this indicator are climate change and natural resource management. Changes in climate alter growing conditions for vegetation (Beck and Goetz 2011, Vickers et al. 2016) and can influence ungulate biomass (Tveraa et al. 2014), even though ungulate biomass is also largely determined by management decisions concerning harvest (Tveraa et al. 2007). Overall, the links to these drivers are assessed as uncertain. Regardless of direction, shifts in the biomass ratio between different plant growth forms and ungulates can indicate a changed ecosystem condition, depending on the cause. Higher abundance of ungulates can reduce the abundance of palatable species (Bråthen et al. 2007; forbs, plants with high nutrient content), thus lowering secondary productivity (production of herbivore biomass) especially in typical Arctic herbivores (reindeer, ptarmigan, various rodents) and hence cause a reduced ecosystem condition. Lower abundance of ungulates can hasten formation of thickets and forests and thus contribute to borealisation of Low Arctic tundra (Bråthen et al. 2017). The understanding of the significance of these changes is assessed as good. Changes in the relative biomass between different growth forms vs. ungulates can be considered of **ecosystem significance** if, for example, i) changes are due to reduction in primary production of palatable plants, ii) changes are due to increased primary production of non-palatable species such as silica rich grasses, ii) changes are due to increased shrubification of habitats among palatable plant species (such as palatable woody plants taking over meadow habitats).

Indicator: Rodents versus carnivorous vertebrates [LI06]
Phenomenon: Decreasing biomass of carnivorous vertebrates relative to rodents [LP06]
Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, rodents display 4 to 5-year population cycles with sufficient regularity and amplitude (peak abundance) to elicit a numerical response in rodent predators (Arctic fox, long-tailed skua, rough-legged buzzard, snowy owl) and contribute to maintaining viable populations of these predators (Ims et al. 2017a, Sundell et al. 2004).

The most important anthropogenic driver of changes in this indicator is climate change, i.e. unstable winters and increased presence of ice at the bottom of the snow pack (basal ice), which lead to a fading out of the small rodent cycles. This link is assessed as certain. Reduced overall abundance of rodents owing to reduced regularity and/or smaller amplitude of rodent cycles, leads to reproductive failure among predators that depend on rodents, and thus to reduced abundance of these predators (Ims et al. 2017a). Moreover, changes in the composition of the rodent community towards a smaller proportion of lemmings (Ims et al. 2011) can lead to a smaller numerical response among predators, as several of them prefer lemmings over other rodents (Hellström et al. 2014). Snowy owl is dependent on high lemming abundance for breeding (Jacobsen et al. 2018a). There is a possibility of threshold effects (e.g. rapid changes/population collapse) due to non-linear functional and numerical responses in the predators (Schmidt et al. 2012). The understanding of the significance of these changes is assessed as good for snowy owl, but less good for the two other species included in this indicator (rough-legged buzzard and long-tailed skua). While the rough-legged buzzard nests all along the Norwegian mountain range and in boreal forests, in addition to tundra, the long-tailed skua is an Arctic species, which can be more sensitive to changes in tundra rodents and may also be negatively affected by shrub encroachment in tundra areas (Henden et al. 2013). Changes in the biomass ratio between rodents and carnivorous vertebrates can be considered of **ecosystem significance** if, for example, i) the shift is caused by weak or absent rodent peaks with consequences at higher trophic levels, or ii) there is a clear reduction in predator abundance despite maintained rodent cycles.

Indicator: Ungulates versus carnivorous vertebrates [LI07]
Phenomenon: Changes in the relative biomass of ungulates and carnivorous vertebrates [LP07]
Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, ungulates are sparse (low biomass) in the tundra in winter. This results in low availability of carcasses and fewer resources for boreal generalist predators (red fox) on the Low Arctic tundra in years with low abundances of small rodents (Killengreen et al. 2011).

The most important anthropogenic drivers of change in this indicator are climate change and resource management, through winter mortality, seasonal movements and population regulation of domestic reindeer herds, and predator control. The latter is linked to the long-term of elimination of large carnivores, likely leading to a mesopredator release (Ehrich et al. 2016). The links to these drivers are assessed as certain, but there will be significant interactions between drivers, rendering it challenging to separate the effects of individual drivers on indicator trends. Increasing populations of semi-domestic reindeer, especially in winter, lead to increased presence of generalist predators such as red fox on the tundra (Henden et al. 2014). Milder winters with extensive basal ice and poor grazing conditions will increase reindeer mortality and shift the ratio towards more generalist predators, while active control of predator populations will shift the ratio towards the ungulates. Climate change (warmer winters; Pasanen-Mortensen et al. 2013) and increased human activity (Elmhagen et al. 2017, Henden et al. 2021a) contribute towards increasing the abundance of generalist predators, such as red fox in the Low Arctic. Larger, more stable populations of generalist predators (red fox) change the trophic structure of the food web (the relationship between predators and prey) with consequences for how it is regulated (i.e. functional changes) and contribute towards borealisation of the food web. Boreal predators have negative effects on ground-nesting birds like ptarmigan (Breisjøberget et al. 2018, Henden et al. 2021a). The understanding of the importance of changes in the relative biomass of ungulates vs carnivorous vertebrates is assessed as less good. Changes in the relative biomass of ungulates vs carnivorous vertebrates can be considered of **ecosystem significance** if, for example, i) the shift constitutes an unequivocal borealisation of the tundra food web, ii) the shift results in changes of ecosystem structure and/or function through increased pressure of red fox on Arctic fox.

In an intact Low Arctic ecosystem 1) rodents display 4 to 5-year population cycles with sufficient regularity and peak abundance to elicit a numerical response in rodent predators, such as the Arctic fox, and contribute to maintaining viable populations of these predators (upper panel), and 2) ungulate population size and grazing pressure contribute to maintaining plant growth forms in a state that is characteristic of Low Arctic tundra. Photos: L.E. Støvern/UiT (upper left), E. Fuglei/NPI (upper right), G. Vie/UiT (lower)

Indicator: Plant growth forms [LI08]

Phenomenon: Changes in the composition of plant growth forms in the plant community [LP08]

Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, the open types of tundra vegetation (ridge, heath, grasslands, and snowbeds) have a combination of functional groups, or plant growth forms, characteristic of Low Arctic tundra (subzones D and E). This includes among vascular plants herbaceous forbs, grasses, sedges, woody deciduous and evergreen prostrate, dwarf and low shrubs (Walker et al. 2012; see the qualitative criteria specified by CAVM; Table 3.1). The relatively low number of vascular plant species in the Low Arctic is thus still representing a wide variety of functional groups, being an indicator of low functional redundancy and indicating shifts in species compositions to also involve shifts in the functional role of vegetation (Wookey et al. 2009).

The most important anthropogenic drivers of change in this indicator are climate change (Myers-Smith et al. 2015, Tape et al. 2006), grazing and browsing by large herbivores (Bråthen et al. 2007, Bråthen et al. 2017), and the feedback processes by the functional compositional changes in the vegetation (Wookey et al. 2009). The links to these drivers are assessed as certain. An important natural driver that may provide an indirect link to climate change is grazing by rodents (Olofsson et al. 2014). Climate change and changes in grazing pressure, as well as changes in competition and growing conditions for vascular plants, can cause shifts in the relative abundance of the different plant growth forms (Bråthen et al. 2018, Bråthen et al. 2007, Elmendorf et al. 2012, Ravolainen et al. 2011). The understanding of the significance of changes in the composition of plant communities in the Low Arctic tundra is assessed as good. Changes can be considered of **ecosystem significance** if, for example, the abundance of unpalatable growth forms such as silica-rich grasses and crow-berry increases relative to growth forms considered palatable such as forbs and silica-poor grasses.

Indicator: Herbivorous vertebrates [LI09]

Phenomenon: Changes in the composition of functional groups within the herbivore vertebrate community [LP09]

Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, lemmings play important and distinct roles because they contribute a sizeable proportion of the total abundance of the rodent community, consisting primarily of Norwegian lemming, grey-sided vole and tundra vole (Ims et al. 2011). Reindeer is the numerically and functionally dominant ungulate in the Low Arctic tundra, and indirect effects on other herbivores, such as ptarmigan, are evident, yet the mechanisms are unknown (Henden et al. 2020, Marolla et al. 2019).

The most important anthropogenic drivers of change for this indicator are climate change, hunting/harvest and resource management (ptarmigan, reindeer, moose). Changes in climate change, resource availability, and hunting/harvest practises can all result in altered relative abun-dances between herbivore species and altered competitive interactions (either direct or indirect competition [i.e. apparent]) The links to these drivers are assessed as certain. In the assessment of this indicator, emphasis is placed on pervasive changes at group level (i.e. within a trophic level) that affect ecosystem function. Special focus is placed on borealisation and loss of typical Arctic species and functions. Substantial reductions in rodent abundance owing to greater irregularity and/or suppression of rodent population cycles in a warmer Arctic lead to i) reduced abundance of rodent-dependent predators (Ims et al. 2017a, Jacobsen et al. 2018a), and ii) vegetation state changes (Olofsson et al. 2014, Ravolainen et al. 2014). Decreasing dominance of the most typical

Arctic rodent species, the Norwegian lemming, contributes to borealisation of the food web and will have consequences for specialised Arctic predators such as snowy owls and Arctic foxes (Ims et al. 2017a, Jacobsen et al. 2018a). Lemmings also counteract dwarf shrub encroachment into snowbeds (Virtanen 2000). The understanding of the importance of these changes is assessed as good. Increased dominance of large herbivores in winter, in combination with more variable winters, can increase the supply of carcasses for boreal scavengers and generalist mesopredators (Henden et al. 2014), thus increasing predation pressure on medium-sized herbivores such as ptarmigan and hare (Breisjøberget et al. 2018, Elmhagen et al. 2010). It can also alter the competition between medium-sized herbivores for limited resources such as willow thickets (Ehrich et al. 2012b, Ims et al. 2007). Because of an increasing population, moose are expanding into the Low Arctic, where they can have considerable impacts on the vegetation, in particular erect shrubs. Changes can be considered of **ecosystem significance** if, for example, i) the presence/dominance of boreal herbivores increases relative to Arctic herbivores, ii) the tundra herbivore community, particularly in winter, becomes increasingly dominated by large herbivores (reindeer, moose).

Indicator: Carnivorous vertebrates [LI10]
Phenomenon: Borealisation of the carnivorous vertebrate community [LP10]
Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, the Arctic carnivores specialised on rodents (Arctic fox, snowy owl, long-tailed skua) constitute a considerable proportion of the vertebrate carnivores in the ecosystem.

The most important anthropogenic drivers of change in this indicator are climate change and natural resource management, which can change the relative abundance of, and competition between, species in the carnivorous vertebrate community. The links to these drivers are assessed overall as certain. There is a focus on borealisation of the community through expansion of generalist species (i.e. red fox and rough-legged buzzard) relative to Arctic specialist species (Arctic fox and long-tailed skua). The Arctic species are affected negatively by suppressed and increasingly irregular rodent population cycles characterised by a smaller proportion of lemming owing to higher temperature (Ims et al. 2017a, Jacobsen et al. 2018a). The red fox benefits from increased resource availability from human activity (Rød-Eriksen et al. 2020) and growing ungulate populations (Henden et al. 2014) and from milder winters in the Low Arctic (Pasanen-Mortensen et al. 2013). It is also conceivable that the politically determined absence of large predators contributes towards a wider distribution of red fox (Ehrich et al. 2016). The link to this last driver is assessed as uncertain. Rough-legged buzzard is also impacted negatively by dampened and irregular small rodent cycles (Fufachev et al. 2019). However, this species has a larger distribution range (boreal forest and shrub tundra) than long-tailed skua that is dependent on open tundra. The understanding of the significance of changes in the carnivorous vertebrate community is assessed as good. Borealisation entails reduced Low Arctic biodiversity and the phenomenon reinforces itself because boreal species (red fox) outcompete Arctic species (Arctic fox) (Elmhagen et al. 2017, Ims et al. 2017a). Moreover, owing to increased dominance of particularly red fox, borealisation will have functional implications, e.g. by increasing predation pressure on ground-nesting birds (Henden et al. 2021a). Changes can be considered of **ecosystem significance** if, for example, i) increased presence of boreal carnivores negatively affects the abundance or presence of Arctic carnivores.

Left panel: The Low Arctic is characterised by tundra vegetation consisting of a combination of functional groups and/or plant growth forms, characteristic for the tundra subzones D and E. Right panel: The red fox benefits from increased resource availability from human activity, growing ungulate populations and from milder winters in the Low Arctic. Borealisation by red fox entails reduced Low Arctic biodiversity and the phenomenon reinforces itself because boreal species outcompete Arctic species, such as the Arctic fox. Photos: E. Soininen/UiT (left), G. Vie/UiT (right)

Indicator: Thicket-forming willows [LI11]
Phenomenon: Changes in abundance of thicket-forming willows in river valleys [LP11]
Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, tall willow thickets (also termed tall shrubs) are a defining form of vegetation for Low Arctic subzone E, particular on sediment flats along rivers, where they form distinctive thickets in mosaics with grassland vegetation (meadows). Here they serve many important trophic and biophysical functions (Ims et al. 2013b).

The most important anthropogenic drivers of change in this indicator are climate change and grazing pressure from large herbivores (Bråthen et al. 2017). The links to these drivers are assessed as certain. The assessment is based on the premise that thicket-forming willow is a central phenomenon along watercourses, serving as both forage (Ravolainen et al. 2011) and as an important habitat for many bird species including ptarmigan (Henden et al. 2011). The continuous supply of nutrients and water in the riverbeds offers good growing conditions for willow thickets, but also for a multitude of plant species, which in turn offer diverse forms of forage and habitat for herbivores and birds. Under the reference condition, riverbeds on the tundra are a mosaic of willow thickets, and species-rich open grassland patches (Ravolainen et al. 2013). Both increasing and decreasing prevalence of thicket-forming willow can indicate state change. Increases of willow thicket in a warmer Arctic, where thickets encroach on species-rich riverbed grasslands, will constitute a poorer ecological condition. Decreases in the amount of willow thicket will reduce the quality of the habitat of many bird species (Ims and Henden 2012), and will also constitute a poorer ecological condition. The understanding of the significance of changes in this indicator is assessed as good. Changes in the prevalence of thicket-forming willow can be considered of **ecosystem significance** if, for example, i) prevalence decreases to a degree such that presence and species diversity in the bird community are negatively affected, ii) prevalence increases (encroachment) to a degree that causes loss of habitat for grassland species.

Indicator: Crowberry biomass [LI12]

Phenomenon: Increased abundance of crowberry in open vegetation types [LP12]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, crowberry does not encroach into new habitats. Crowberry is currently the dominant plant species on Low Arctic tundra in Finnmark (e.g. Killengreen et al. 2007).

The most important anthropogenic driver of change of crowberry abundance is climate change; grazing has little significance (Bråthen et al. 2007). Crowberry increases in abundance with temperature increases (Bråthen et al. 2018, Shevtsova et al. 1997, Tybirk et al. 2000). The link to temperature as an anthropogenic driver is assessed as certain. However, in the ecotone, crowberry can be depleted by moth outbreaks (Karlsen et al. 2013). Also, crowberry is declining with increased disturbance activities by lemmings (Tuomi et al. 2019), hence there are patches of reduced or arrested crowberry abundance. Crowberry has chemical properties that reduce primary and secondary production of other species (Bråthen et al. 2018), even in sites where the plant itself does not grow (Pilsbacher et al. 2020). Furthermore, increased abundance of crowberry is related to reduced species diversity among other plants (e.g. Bråthen et al. 2018). Crowberry can thus cause state changes in both vegetation and the ecosystem. The understanding of the significance of increasing crowberry abundance is assessed as good. A temperature-driven increase in crowberry abundance is considered of **ecosystem significance** if, for example, i) it results in reduced primary production and/or reduced species diversity among other tundra species.

Indicator: Mountain birch in forest-tundra [LI13]

Phenomenon: 1) Weakened recruitment after moth outbreaks [LP13] and
2) Sustained reduction of forested area and/or forest density [LP14]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, multi-stemmed mountain birch is the tree species that defines and dominates the forest-tundra. It is periodically exposed to moth outbreaks that do not exceed the forest's ability to regenerate.

The most important anthropogenic drivers of changes in this indicator are climate change, through altered growing conditions (Beck and Goetz 2011, Vickers et al. 2016) and grazing by managed herbivores (Bråthen et al. 2017). Climate change can also affect the indicator indirectly through intensification of insect outbreaks (Jepsen et al. 2013, Jepsen et al. 2009b), leading to increased mortality of mountain birch. These links to anthropogenic drivers are assessed as certain, but the complex interactions between climatic and biotic drivers (i.e. growing conditions and grazing; Vindstad et al. 2019), and between biotic drivers (moth outbreaks and reindeer grazing; Biuw et al. 2014), which operate on varying scales, make it challenging to separate the effects of the individual drivers. The understanding of the importance of changes in recruitment (regrowth) for future forested area/tree density is assessed as less good. The uncertainty is particularly linked to saplings, and how many and how quickly new trees must be established in order to maintain the forest's structural characteristics over time. The understanding of how potential long-term changes in forested area/forest density affect the ecosystem in forest-tundra and tundra is also assessed as less good. Weakened recruitment and loss of forested area and/or forest density in the ecotone are signals that climatic or biotic (for herbivory) tolerance levels have been exceeded, and thus a degraded forest-tundra condition. Weakened recruitment (regrowth) after moth outbreaks, leading to sustained loss of forested area/forest density can be considered of **ecosystem significance** if, for example, i) it leads to loss of habitat/forage and changes in land use patterns of grazers and game animals (Jepsen et al. 2013, Vindstad et al. 2015, Vindstad et al. 2014), ii) it affects the reflective properties (albedo) of forest-tundra on a regional scale (Biuw et al. 2014, Cohen et al. 2013).

Indicator: Lemming abundance [LI14]
Phenomenon: Less frequent, less distinct peaks in the lemming cycle [LP15]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, lemming cycles occur regularly on the Low Arctic tundra, especially at high elevations (> 200 masl), with a sufficient regularity and amplitude to support viable populations of lemming-dependent predator species (i.e. Arctic fox and snowy owl), and to maintain snowbed vegetation through grazing.

The most important anthropogenic driver of change in this indicator is climate change. Lemming is vulnerable to a mild winter climate, particularly decreasing snow cover and increased presence of hard snow layers and basal ice (Berteaux et al. 2017, Kausrud et al. 2008). This link is assessed as <u>certain</u>. The understanding of the importance of changes in this indicator is assessed as <u>good</u>. Reduced abundance of lemming owing to greater irregularity and/or suppression of lemming cycles in a warmer Arctic results in decreased reproductive success among Arctic lemming specialists, particularly Arctic fox and snowy owl, and thus a degraded condition (Ims et al. 2017a). For example, absence of a single lemming peak year (which means a seven-year period of low lemming abundance), can have a decisive negative impact on the viability of an Arctic fox population with a generation time of about four years. Such changes in lemming cycles will also affect the vegetation characteristic of snowbeds, which is in part maintained by regular perturbation by lemming (Olofsson et al. 2014, Virtanen 2000). The assessment of this indicator must take into consideration the peak years' frequency, season-specific amplitude and spatial synchronicity. Seasonality is important because the predators are most sensitive to resource availability in spring. The underlying data should have adequate temporal coverage (at least 15–20 years) to permit documentation of changes. Fewer and/or less pronounced lemming peaks can be considered of **ecosystem significance** if, for example, i) lemming peaks are too small or infrequent to maintain populations of lemming specialists, ii) lemming peaks are too small or infrequent to contribute towards maintaining characteristic snowbed vegetation.

Indicator: Ptarmigan density [LI15]
Phenomenon: Low and/or decreasing abundance of willow ptarmigan [LP16]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, willow and rock ptarmigan are the only native herbivorous bird species in the Low Arctic tundra in winter; the populations co-vary with rodent cycles, showing regular population peaks where their abundance provides a basis for a viable gyrfalcon population and sustainable hunting.

The most important anthropogenic drivers of change in this indicator are climate change, e.g. through changes in seasonality and precipitation patterns during critical periods (Erikstad and Andersen 1983, Henden et al. 2020) and harvest/hunting (Henden et al. 2020, Pedersen et al. 2004, Sandercock et al. 2011). Climate change also exert indirect effects on the indicator through intensified insect outbreaks that devastate ptarmigan food plants (Henden et al. 2020). Climate-induced dampened amplitude or loss of rodent population cycles (Kausrud et al. 2008), as well as increased primary productivity (greening) and the increased availability of ungulate carcasses act to increase the impact of generalist predators on ground breeding birds (including ptarmigan)

(Henden et al. 2014, Ims et al. 2019, Marolla et al. 2019). Increased availability of carcasses likely results from a combination of management-driven increases in domestic reindeer populations and increased reindeer mortality owing to changes in winter climate. The links to some anthropogenic drivers (climatic and biotic) are assessed as less certain, even though the relationship with rodent population dynamics and the general significance of predation for productivity and survival is assessed as certain (Fuglei et al. 2019a, Henden et al. 2021a, Henden et al. 2017). Ptarmigan populations have decreased substantially in recent decades, to the point that ptarmigans were red-listed as "near threatened" (Henriksen and Hilmo 2015). Compared to historic data (Hjeljord 2015), the current populations are considered small and thus in poor ecological condition. This also appears to be representative of the Low Arctic parts of Finnmark, which have considerably lower population densities than Low Arctic parts of Russia (Ehrich et al. 2012a). Further dampened or less regular cycles result in lower reproductive success for ptarmigan during rodent peak years (Henden et al. 2020). Further increase in primary (greening) and secondary productivity (e.g. carrion) that act to increase the abundance of generalist predators is expected to decrease the productivity of ground-breeding bird populations (Henden et al. 2014, Ims et al. 2019). Changes in seasonality in the form of mismatch between moulting and snow cover duration can render ptarmigan more susceptible to predation during the transition between summer and winter, leading to lower survival of adults and reduced recruitment to the breeding population (Henden et al. 2020). Absence of ptarmigan population peaks can lead to absence or reduced numbers of ptarmigan specialist predators (gyrfalcon). Sustained low densities and weak productivity owing to strong predation and adverse weather indicate a poor ecological condition. Overall, the understanding of the importance of future changes in this indicator is assessed as less good owing to the complexity of the drivers. Low abundance of willow ptarmigan can be considered of **ecosystem significance** if, for example, i) the population no longer supports viable populations of ptarmigan specialists (gyrfalcon), ii) the population no longer supports sustainable hunting.

Left panel: Tall willow thickets are a defining form of vegetation for Low Arctic subzone E, particularly on sediment flats along rivers, where they form distinctive thickets in mosaics with grassland vegetation (meadows). Here they serve many important trophic and biophysical functions. Right panel: Multi-stemmed mountain birch is the tree species that defines and dominates the forest-tundra. It is periodically exposed to moth outbreaks, which recently have been severe and exceeded the forest's ability to regenerate in some areas. Photo: E. Soininen/UiT (left), J. Iglhaut/NINA (right)

Indicator: Geometrid moth outbreaks [LI16]

Phenomenon: 1) Invasion of new moth species that establish as outbreak species in the forest-tundra ecotone [LP17], 2) Establishment and spread of new moth species in willow shrub tundra far from birch forest [LP18]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, the autumnal moth is the only outbreaking moth species in the forest-tundra ecotone. Population abundance peaks of the autumnal moth occur cyclically at 9–10-year intervals. During some peaks, moth abundance reaches outbreak levels, defined here as the abundance required to cause visible defoliation of the mountain birch host plant (approximately 20% defoliation). The duration of these outbreaks normally does not exceed three consecutive years. Autumnal moth outbreaks are restricted to the forest-tundra, with minimal spill-over into willow shrub tundra (Ruohomäki et al. 2000, Tenow 1972).

The most important anthropogenic driver of change in this indicator is climate change. Rising temperatures seem to have allowed the winter moth, which is a southern and more thermophilic species than the autumnal moth, to expand its outbreak range northwards and eastwards (Jepsen et al. 2008). Although the specific mechanism is not fully established (cf. Jepsen et al. 2011) the link to climate is <u>certain</u>. The understanding of the importance of the establishment of the winter moth as a new outbreak species in the forest-tundra ecotone (LP17) is assessed as <u>good</u>. The establishment of the winter moth has led to increased overlap with the outbreak range of the autumnal moth, resulting in a more species-rich community of outbreaking moth defoliators. This has led to longer lasting and more frequent outbreaks that impose a greater cumulative defoliation pressure on the mountain birch forest. It has also led to cascading impacts on ground layer vegetation, vertebrate herbivores, passerine birds, willow ptarmigan, and other insect communities (Henden et al. 2020, Jepsen et al. 2013, Vindstad et al. 2015, Vindstad et al. 2014). It is a signal of a degraded forest-tundra condition when the forest tolerance thresholds to defoliation are exceeded and post-outbreak forest recovery is slow (Vindstad et al. 2019). The indicator must therefore be viewed in connection with the indicator *Mountain birch in forest-tundra*. At the interface between forest-tundra and willow shrub tundra, the establishment of the highly polyphagous winter moth (LP18) has also led to increased spill-over of outbreaks from birch to willow shrubs and hence the climate change link for this indicator is also <u>certain</u>. However, the understanding of the importance of this change in the indicator is assessed as <u>less good</u>. The indicator must be viewed in concert with the indicator *Thicket-forming willows*. Changes in geometrid moth outbreaks can be considered of **ecosystem significance** if, for example, i) cumulative defoliation increases to the extent that forest-tundra tolerance thresholds are exceeded, leading to widespread declines in tree cover and ii) outbreaks in willow shrub tundra lead to widespread declines in willow shrub prevalence.

Indicator: Semi-domestic reindeer abundance [LI17]

Phenomenon: Change in abundance of semi-domestic reindeer [LP19]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, semi-domestic reindeer is a functionally important herbivore in Low Arctic tundra. With a population size adapted to the carrying capacity of the grazing grounds, the reindeer contribute towards maintaining the tundra vegetation's characteristic (intact) condition, counteract overgrowth by thicket-forming willow and trees (expansion of forest-tundra) in meadows, and provide the most significant ecosystem service for reindeer herders and the Sámi population. In accordance with their natural migration pattern, semi-domestic reindeer are in the reference condition expected to be present at low abundances in winter in the Low Arctic tundra on the coastal peninsulas of Finnmark, and thus expected to have limited trophic functions (e.g. as grazer or as carcass for opportunistic predators/scavengers) on the tundra during this season (Henden et al. 2014, Tveraa et al. 2013).

The most important anthropogenic drivers of change in this indicator are climate change and resource management decisions related to reindeer population sizes and harvest levels (Hausner et al. 2011, Tveraa et al. 2007, Tveraa et al. 2014). These links are assessed as <u>certain</u>, despite uncertainty related to the significance of winter snow conditions. Overabundance and underabundance of reindeer can contribute to a degraded ecological condition through the effects of grazing on the vegetation. Low grazing pressure on ligneous species can lead to a shrubification of tundra (Bråthen et al. 2017), whereas high grazing pressure can lead to vegetation state changes towards dominance of less palatable growth forms (Bråthen et al. 2007) and low plant productivity relative to the ungulates' needs, thus lowering the body mass and calf rate of reindeer. This indicator should therefore be viewed in context of other indicators, including *Thicket-forming willows, Mountain birch in forest-tundra, Plant growth forms, Reindeer calf body mass,* and *Reindeer calf rate*. The understanding of the importance of changes in reindeer abundance for the condition of the ecosystem is assessed as <u>good</u>. Changes in the abundance of reindeer can be considered of **ecosystem significance** if, for example, i) underabundance leads to shrubification, especially along riverbeds, resulting in loss of typical tundra habitats, ii) overabundance leads to low or decreasing calf rate, iii) overabundance leads to lower body masses.

Indicator: Semi-domestic reindeer calf body mass [LI18]
Phenomenon: Low or decreasing semi-domestic reindeer calf body mass [LP20]
Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, average reindeer calf body mass, measured as slaughter weights, stays above recommended values for "ecologically sustainable reindeer husbandry" (Landbruks- og matdepartementet 2008).

The most important anthropogenic drivers of change in this indicator are climate change and resource management decisions related to population sizes and harvest levels (Hausner et al. 2011, Tveraa et al. 2007, Tveraa et al. 2014). The links to these drivers are assessed as <u>certain</u>. Low or decreasing calf body mass at slaughter signals that a population has difficult living conditions. This can be attributed to factors that are directly caused by humans, such as increased population density owing to decreased harvest levels or factors that work indirectly, such as changes in climatic conditions which in turn affect the grazing grounds. This indicator should therefore be viewed in the context of several other indicators, including *Reindeer abundance, Reindeer calf rate, Onset of spring greening, Maximum vegetation productivity, Plant growth forms*, and relevant abiotic indicators. This will allow a more comprehensive assessment of the cause of a deviation from the reference condition. The understanding of the importance of changes in calf body mass is assessed as <u>good</u>. Low or decreasing reindeer calf body masses can be considered of **ecosystem significance** if, for example, i) calf body masses are low over time or consistently decreasing.

Indicator: Semi-domestic reindeer calf rate [LI19]

Phenomenon: Low or decreasing semi-domestic reindeer calf rate [LP21]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, the calf rate is sufficient to maintaining populations at levels set by management goals with respect to animal numbers and calf body masses (Landbruksdirektoratet 2020).

The most important anthropogenic drivers of change in this indicator are climate change and resource management decisions related to population sizes and harvest levels (Hausner et al. 2011, Tveraa et al. 2007, Tveraa et al. 2014). The links to these drivers are assessed as <u>certain</u>. Low or decreasing calf rate signals that the reindeer population has difficult living conditions. This can be attributed to factors that are directly caused by humans, such as increased population density through decreased harvest levels, or factors that work indirectly, such as changes in climatic conditions, and changes in the management of predators, which in turn affect the predator communities. This indicator should therefore be viewed in the context of several other indicators, including *Semi-domestic reindeer abundance, Onset of spring, Maximum vegetation productivity, Plant growth forms*, and relevant abiotic indicators (e.g. *Basal ice*) that will allow a more comprehensive assessment of the cause of a deviation from the reference condition. The understanding of the significance of changes in calf rate is assessed as <u>good</u>. Low or decreasing semi-domestic reindeer calf rate can be considered of **ecosystem significance** if, for example, i) the rate is low over time or consistently decreasing.

Indicator: Red fox camera index [LI20]

Phenomenon: Increased or high proportion of days with red fox captures by camera traps [LP22]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, established red fox populations are distributed only in the most productive Low Arctic areas (e.g. coastal lowland).

The most important anthropogenic drivers of change in this indicator are climate change and resource management/harvest. The links to these drivers are assessed as <u>certain</u>. The growth of the red fox population is driven mainly by increased resource availability (Elmhagen et al. 2017) owing to increased productivity in general (Killengreen et al. 2007), increased human activity (increased access to food associated with highways; Rød-Eriksen et al. 2020), and increasing populations of ungulates, especially in winter (Henden et al. 2014). In addition, warmer winters are expected to be beneficial for the red fox (Pasanen-Mortensen et al. 2013). Increased presence of red fox, particularly at higher/more barren parts of the productivity gradient, leads to borealisation of communities and thus a degraded ecological condition. The camera index is affected by both abundance and activity, which can be compared between Arctic fox and red fox (Hamel et al. 2013). The understanding of the importance of increased red fox densities for Arctic fox and in part also on ground-nesting birds is considered <u>good</u> (Angerbjörn et al. 2013). For red fox, an increased proportion of days with red fox captures by camera traps can be considered of **ecosystem significance** if, for example, i) the increase occurs in inland parts of the tundra (far from the coast), the most barren parts of the productivity gradient (areas at higher elevations), ii) increased presence of red fox results in increased competition with Arctic fox for resources and denning sites.

Indicator: Large predator abundance [LI21]

Phenomenon: Low abundance of wolverines and wolves in Low Arctic tundra [LP23]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, wolverines and wolves are large predators expected to be present in an intact Low Arctic ecosystem in Northern Norway. Together with the lynx and brown bear, they form the functional group of large predator species in Norway. They also have habitat requirements compatible with the forest-tundra ecotone and boreal ecosystems further south. The distribution and population sizes of large predators are strictly regulated in Norway to reduce human conflicts, in particular due to predation on domestic animals. Wolves were common in Finnmark in the latter part of the 19th century (Collett 1911), but hunted to extinction by the 1980s. It is not a national policy to have wolves in Finnmark — the national management strategy is to have wolves in south-east Norway only (Miljødirektoratet 2021). The wolverine population in Norway has been low throughout the 19th and 20th century, until protected in 1982, probably due to extensive hunting (Bestandsstatus – jerv 2021, Skjenneberg and Slagsvold 1968). In the Low Arctic climatic zone in northern Norway, semi-domesticated reindeer and farmed animals have priority over wolverine conservation. Wolverines are given priority over domestic animals in a zone further south, closer to the border to Finland, and for Finnmark the national management goal for wolverines is three successful reproductions per year (Bestandsstatus – jerv 2021). The population size of wolverine is regulated using licenced hunting and culling.

The most important anthropogenic driver of change in this indicator is political management decisions implemented by licenced hunting and culling of large predators. The link is assessed as certain. A change in the national management goal for wolverine and wolf is needed to allow higher densities of wolverines, and wolves to re-establish in Low Arctic tundra. The understanding of the importance of changes in this indicator is assessed as good. The wolverine is categorised as “endangered” and the wolf as “critically endangered” on the Norwegian Red List. Absence of wolves and number of reproducing female wolverines, kept close to three per year in Finnmark, is considered of **ecosystem significance**.

Indicator: Snowbed encroachment [LI22]

Phenomenon: Increasing presence or cover of woody plants in snowbeds [LP24]

Ecosystem characteristic: Landscape-ecological patterns

Under the reference condition, snowbed vegetation is an important but patchily distributed habitat type in the tundra ecosystem; it is maintained by long-lasting snow cover and grazing, especially by lemming.

The most important anthropogenic driver of change in this indicator is climate change, through changes in the duration of snow cover (Björk and Molau 2007, Henden et al. 2021a). The link to this driver is assessed as certain. Snowbeds are an important, but patchily distributed vegetation state, maintained by long-lasting snow cover and grazing, especially by lemming (Olofsson et al. 2014, Virtanen 2000), and/or by allochthonous allelopathy by crowberry growing in surrounding heath (Pilsbacher et al. 2020). However, snowbeds are important grazing grounds also for managed herbivores (Mysterud and Austrheim 2014), hence large herbivores are also expected to impact snowbeds. Climate change can exert an indirect effect on this indicator through changes in lemming dynamics. The understanding of the significance of changes in snowbeds in the Low Arctic ecosystem is assessed as less good. Shrub encroachment into snowbeds affects the availability of forage for large and small herbivores, and also affects plant biodiversity (Björk and Molau 2007).

State changes from snowbeds to heath vegetation (dominated by dwarf shrubs), grassland, or thicket vegetation (dominated by tall grasses, herbs, or willow) are expected results of lower grazing pressure from lemming (owing to absence or suppression of lemming population peaks), increasing temperatures, and/or shorter duration of snow cover. This is a clear sign of a less Low Arctic and thus worsened ecological condition. State changes of snowbeds can be considered of **ecosystem significance**, for example i) if vascular plants characteristic of heath (e.g. dwarf shrubs or matgrass *Nardus stricta*) or grassland (tall grasses or herbs) increasingsly become established in the snowbeds.

Indicator: Bioclimatic subzones [LI23]
Phenomenon: Decreasing total area that meets climate criteria for Low Arctic tundra zones D and E [LP25]

Ecosystem characteristic: Landscape-ecological patterns

Under the reference condition, the Low Arctic tundra belongs — in purely climatic terms — to bioclimatic subzones D (Southern Arctic tundra zone) and E (Arctic shrub-tundra zone), and only rarely crosses over into the north-boreal zone (CAVM Team 2003, Epstein et al. 2004).

The most important anthropogenic driver of change in this indicator is climate change. The indicator is based on average July temperature with increasing temperatures leading to a northward shift of the boreal zone, thus reducing the area that climatically belongs to the Low Arctic subzones D and E. IPCC concludes that it is *extremely likely* that more than half of the global warming observed between 1950 and 2010 was caused by anthropogenic factors (IPCC 2014). The link to anthropogenic factors is therefore assessed as certain for all temperature-derived indicators, including the bioclimatic subzones. Decreasing total area that meets climate criteria for Low Arctic tundra zones D and E indicates a degraded condition because it means that these regions will eventually support north-boreal ecosystems. However, the understanding of the importance of changes in this indicator is assessed as less good, since we lack fundamental knowledge about how, and how rapidly, current abiotic changes will affect the characteristics of the tundra ecosystem, including central trophic interactions. Changes can be considered of **ecosystem significance** if, for example, i) entire bioclimatic subzones cease to exist ("vanishing climates"; Hoffmann et al. 2019, Tang et al. 2014, Williams et al. 2007), ii) the area of an subzone is reduced to the extent that it leads to area sized-induced loss of zone-specific species functions, iii) increased presence/extent of boreal ecosystem features (species, functions) to the detriment of Arctic features.

Indicator: Wilderness areas [LI24]
Phenomenon: Decreasing total area of wilderness areas [LP26]

Ecosystem characteristic: Landscape-ecological patterns

Under the reference condition, Low Arctic tundra regions are essentially unaffected by major technical/industrial installations.

Development is the only driver of changes in this indicator. The indicator measures areas that are unaffected by (i.e. > 1 km or > 5 km distant from) construction of major technical infrastructure. The link to this driver is therefore assessed as certain. Loss of wilderness areas, and the resulting fragmentation of natural habitats, can affect land use patterns and migration routes of large grazing animals (Wolfe et al. 2000), and is therefore seen as a development towards a degraded ecological condition. However, various studies demonstrate huge contrasts in terms of whether a negative effect of a technical installation can be found, and in terms of how strong that effect is on focal ecosystem components (Skarin and Ahman 2014). The understanding of the significance of changes in this indicator is therefore assessed as <u>less good</u>. This also means that, even though loss of wilderness areas must in itself be seen as a worsening of the ecological condition, it is not considered possible to set an absolute threshold for when this loss becomes critical in general terms. It will depend on the type of perturbation, how and where it is carried out relative to key habitats such as reindeer grazing and calving grounds. Loss of wilderness area can be considered of **ecosystem significance** if, for example, i) the area lost is so extensive as to affect movement patterns or productivity of large herbivores, particularly semi-domestic reindeer.

Low Arctic tundra in the interior of Varanger Peninsula in northeast Finnmark has over the last decades, under increased summer temperatures, shifted from bioclimatic subzone D to subzone E. Photo: R.A. Ims/UiT

Indicator: Plant communities [LI25]
Phenomenon: Increased proportion of boreal and woody species at the expense of Arctic and herbaceous species [LP27]
Ecosystem characteristic: Biological diversity

Under the reference condition, Arctic-alpine plant species and a set of different functional groups are common in plant communities in the Low Arctic tundra vegetation (subzones D and E), and the species richness is in a steady state or even increasing.

The most important anthropogenic driver of change in this indicator is climate change. Plant species are tracking their temperature niche as indicated by the upward and northward changes in species distributions in response to a warming Arctic (Chen et al. 2011). A thermophilisation of the tundra flora is happening, where warm adapted species replace cold adapted species (Elmendorf et al. 2015, Gottfried et al. 2012). However, the species pool of the Low Arctic tundra is not fully saturated (Rijal et al. 2020), hence an increase in species richness is nevertheless expected. The link to this driver is therefore assessed as <u>less certain</u>. The borealisation of the Low Arctic tundra in terms of shrub encroachment indicates that conditions are especially improving for woody taxa, a phenomenon that potentially can be counteracted by herbivores (Bråthen et al. 2007). Finally, the low functional redundancy of the Low Arctic tundra vegetation (Wookey et al. 2009) suggests continuous presence of species in all functional groups is a prerequisite to sustain ecosystem functionality. The understanding of the significance of these changes is assessed as good. Changes in the biodiversity of plant communities are considered of **ecosystem significance** if, for example, i) species richness or diversity is declining, ii) the relative number of species and/or the biomass of plant species with a strict Arctic-alpine distribution is declining relative to plant species which also are common in the boreal and nemoral zone, iii) the relative number of species and/or the biomass of woody taxa are replacing that of herbaceous taxa, iv) the proportional number of species and biomass of functional groupings are shifting.

Indicator: Arctic fox abundance [LI26]
Phenomenon: Absence of sustained increase in Arctic fox population despite conservation efforts [LP28]

Ecosystem characteristic: Biological diversity

Under the reference condition, Arctic fox populations are viable in all bioclimatic subzones in the Arctic tundra. Historic records as well as a large number of old Arctic fox dens indicate that Low Arctic Finnmark has had a large breeding population stretching from the coast to higher elevations with contiguous tundra vegetation (Ims et al. 2017a).

The most important anthropogenic driver of change in this indicator is at present indirect effects of climate change. This link is assessed as certain. Arctic fox is a typical Arctic species, which is critically endangered in Norway (Eide et al. 2017). In a historic perspective, hunting has been assumed to be the most important anthropogenic driver, but the Arctic fox has been protected in Norway since 1930. Until the 1980s, the species was considered common in the Low Arctic parts of eastern Finnmark (Ims et al. 2017a). The population subsequently declined sharply in number and range, and initiation of conservation efforts (control of red fox) on Varanger Peninsula in 2005 did not alter this downward trend. In 2017, the population was assessed as being near extinction (Ims et al. 2017a). In 2018, additional conservation efforts for Arctic fox on Varanger Peninsula were initiated, including release of foxes from a breeding station, and supplementary feeding. The understanding of which drivers threaten the Arctic fox population is good, for Fennoscandia overall and for Norwegian Low Arctic specifically (Angerbjörn et al. 2013). Rising temperatures, a consequent general increase in productivity, and high abundance of large herbivores are expected to be advantageous particularly for red fox, but not for Arctic fox (Elmhagen et al. 2017). Less stable winter climate exerts a negative impact on Arctic fox through dampened lemming cycles (Ims et al. 2011), which leads to absent reproduction or to small litters (Ims et al. 2017a). Increased infrastructure development can also benefit red fox through increased access to food associated with roads, cabins, and tourism (Rød-Eriksen et al. 2020). Competition from a growing red fox population displaces the Arctic fox from dens even in inland tundra areas (Killengreen et al. 2007). Based on the extremely small population size, this indicator is at present assessed as being in a degraded ecological condition. Future developments will depend on how the population responds to ongoing conservation efforts and how the anthropogenic drivers of the decline will develop further. Lack of population growth, despite intense efforts indicates that the ecosystem, for example owing to absence of lemming peak years or high red fox density (despite efforts at population control), can no longer support an Arctic fox population. Absence of a sustained increase in the Arctic fox population (the number of breeding pairs) despite conservation efforts, will be considered of **ecosystem significance**, regardless of cause, because it will in practice mean that the species becomes extinct in Low Arctic tundra.

Indicator: Arctic fox litter size [LI27]
Phenomenon: Small or decreasing litter size of Arctic fox [LP29]
Ecosystem characteristic: Biological diversity

Under the reference condition, Arctic fox litter size is strongly influenced by the availability of lemming; large litters (> 9) in lemming peak years are typical of the inland, lemming related Arctic fox ecotype (Fuglei and Ims 2008) and give a population growth rate that on average is positive (Henden et al. 2008)

The most important anthropogenic driver of changes in this indicator is indirect effects of climate change. This link is assessed as <u>certain</u>. In the parts of the Arctic where the Arctic fox is specialised on lemming, there are strong correlations between litter size and phase of the lemming cycle. Large litters (> 9 pups) are normal in peak lemming years, but the average over all phases of the cycle is about 6-8 pups in Arctic regions for which enough data are available for such calculations (Tannerfeldt and Angerbjorn 1998). There is also a strong correlation between Arctic fox litter size and lemming density in the Norwegian Low Arctic, but the average litter size is at present considerably smaller than in other lemming-dependent populations (Ims et al. 2017a). In persistently small populations, inbreeding may also play a role in decreasing litter size (Noren, et al. 2016). Small litters owing to lack of lemmings or other conditions, are a clear indication of a degraded ecological condition. Based on the extremely low reproduction this indicator is at present assessed as being in a degraded ecological condition. The understanding of which factors regulate Arctic fox litter size is <u>good</u>. For Arctic fox small litters can be considered of **ecosystem significance** if, for example, litter size i) is generally smaller than what is normal among lemming-dependent Arctic fox populations or ii) does not respond to management actions such as control of the red fox population and supplementary feeding.

Indicator: Arctic fox camera index [LI28]
Phenomenon: Absence of sustained increase in the proportion of days with Arctic fox captures by camera traps despite conservation efforts [LP30]
Ecosystem characteristic: Biological diversity

The reference condition is the same as for the indicator *Arctic fox abundance*, and the anthropogenic drivers are the same as for other indicators pertaining to Arctic fox. The links to these drivers are assessed as <u>certain</u>. Unlike the indicator *Arctic fox abundance*, the camera index will be affected by both abundance and activity levels of Arctic fox, thus also reflecting the abundance of the non-breeding part of the population. The indicator will also be affected by competition with red foxes for reindeer carcasses as a resource, and may thus be related to the ratio between the two species in winter (Hamel et al. 2013, Killengreen et al. 2012). The understanding of changes in this indicator for the state of the Arctic fox population and consequently for Arctic biodiversity is <u>good</u>. For Arctic fox, absence of an increase in the proportion of days with Arctic fox captures by camera traps can be considered of **ecosystem significance** if, for example, i) this occurs in inland parts of the tundra/the most barren parts of the productivity gradient, ii) it can be linked to increasing presence of red fox, and iii) it is related to the absence of sustained increase in Arctic fox population despite conservation efforts.

Indicator: Snowy owl abundance [LI29]

Phenomenon: Absence of breeding snowy owls during the majority of peak rodent years linked to low lemming abundance [LP31]

Ecosystem characteristic: Biological diversity

Under the reference condition, the presence of breeding snowy owls in the Low Arctic tundra is closely linked to regularly occurring lemming peak years. The Low Arctic part of Finnmark has historically been assumed to be one of the most important breeding grounds for snowy owl in Norway, but historic data showing the size of the breeding population or the regularity of breeding are lacking (Jacobsen et al. 2018a).

The most important anthropogenic driver of change in this indicator is climate change (acting indirectly), and the link is assessed as <u>certain</u>. Snowy owl initiates breeding (numeric response) when the abundance of lemming in spring exceeds a threshold level (Gilg et al. 2003). In the parts of the Norwegian Low Arctic that offer suitable breeding habitats for snowy owl (e.g. inland or higher altitude stretches of coastal peninsulas), high abundance of grey-sided vole and/or tundra vole does not appear to compensate for the absence of the Norwegian lemming. Milder and less stable winters that make lemming peaks less frequent and/or smaller, especially in spring, will result in similarly less frequent peaks and lower abundance of snowy owl (lack of numeric response). The understanding of the importance of changes in this indicator is assessed as <u>good</u>. Snowy owl is listed as "endangered" on the Norwegian Red List. Snowy owls that nest in the Norwegian Low Arctic belong to a common Norwegian-Russian population (Jacobsen et al. 2018a). Absence of breeding pairs of snowy owl in Norwegian Low Arctic during lemming peaks is considered of **ecosystem significance** regardless of cause.

Indicator: Snowy owl fecundity [LI30]

Phenomenon: Low and/or decreasing snowy owl clutch size during peak rodent years [LP32]

Ecosystem characteristic: Biological diversity

Under the reference condition, the presence of breeding snowy owl in the Low Arctic tundra is closely linked to regularly occurring lemming peak years. The Low Arctic part of Finnmark has historically been assumed to be one of the most important breeding grounds for snowy owl in Norway, but historic data showing clutch size are lacking (Jacobsen et al. 2018a).

The most important anthropogenic driver of change in this indicator is climate change (acting indirectly), and the link is assessed as <u>certain</u>. This indicator is closely linked to *Snowy owl abundance*. Reproductive success of snowy owl is dependent on lemming abundance in spring and early summer being sufficient to allow the chicks to survive to maturity (Potapov and Sale 2012). Loss of eggs and chicks owing to large populations of generalist predators (eagles and red fox) can probably also contribute to reduced reproductive success. The understanding of the importance of changes in this indicator is assessed as <u>good</u>. Lack of reproductive success in years when snowy owl pairs have initiated breeding is considered of **ecosystem significance** regardless of cause.

Indicator: Bird communities [LI31]

Phenomenon: Decreasing abundance and species diversity among open tundra species [LP33]

Ecosystem characteristic: Biological diversity

Under the reference condition, the composition of the bird community is dominated by, and in part defined by, several species typical of open tundra habitats.

The most important anthropogenic driver of change in this indicator is climate change (direct and indirect effects). Climatic drivers can lead to phenological mismatch, especially among birds that migrate long and medium-long distances. The indicator can also be affected indirectly when changes in rodent dynamics (i.e. less frequent peak years) lead to increased predation by reducing the frequency of years with low predation pressure. There is also evidence that increased primary productivity increases predation on the nests of ground-breeding birds, in particular, in the colder bioclimatic sub-zones of the Low Arctic tundra (Ims et al. 2019). The links to anthropogenic drivers are assessed as certain, especially the relationship with phenological mismatch, which affects migration and access to food supply during nesting (Carey 2009, Crick 2004, Miller-Rushing et al. 2010). Species that are specifically adapted to the habitat structures, competitive, or trophic conditions (nutrient supply and predation pressure) in intact tundra ecosystems are expected to decline in a warming Arctic (Lehikoinen et al. 2019, Lehikoinen et al. 2014). In contrast, species with wide distribution ranges (i.e. more boreal species associated with willow thickets in tundra) are expected to have a flexibility that makes them resilient towards many drivers, and they may become competitively dominant under altered environmental conditions. The understanding of the significance of changes in this indicator is assessed as less good. Change in bird communities can be considered of **ecosystem significance** if, for example, i) tundra species that are normally abundant and that define Low Arctic bird communities are lost, and ii) the communities are gradually being dominated by species with wide distribution ranges.

Upper panels: Chicks of rock ptarmigan and rough-legged buzzard, which are characteristic species of Low Arctic tundra. Lower panels: Arctic meadows, characterised by a set of Arctic-alpine plant species and different functional groups, are at present influenced by shrub encroachment, indicating a borealisation of the Low Arctic tundra. Photos: G. Vie/UiT (upper left), R. A. Ims/UiT (upper right), E. Soininen/UiT (lower left, lower right)

Indicator: Days with extreme cold [LI32]

Phenomenon: Decreasing frequency of days with extreme cold [LP34]

Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. IPCC concludes that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C per decade (high confidence) (Allen et al. 2018). Arctic surface air temperature has increased by more than twice the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming (Meredith et al. 2019). The link to anthropogenic drivers is therefore assessed as <u>certain</u> for all temperature-derived indicators, including the number of *Days with extreme cold*. Extreme cold can protect areas against local moth outbreaks by increasing the mortality of overwintering eggs (Ammunet et al. 2012, Nilssen and Tenow 1990, Tenow and Nilssen 1990). The limit of 30°C is indicative of extreme cold, but is not an absolute limit of tolerance, as the cold tolerance of the eggs varies between species and depending on the time period in winter. Lack or very low frequency of such temperatures will, however, indicate that extreme cold is probably not a limiting factor for the extent of moth outbreaks and other invasive or range expanding invertebrates. The understanding of the significance of changes in extreme cold is assessed as <u>good</u>, but we lack knowledge about how prolonged absence of extreme cold will affect the spread of new boreal species into Low Arctic tundra. Declining frequency of days with extreme cold can be considered of **ecosystem significance** if, for example, i) there is an inverse relationship between the incidence of moth outbreaks and the frequency of days with extreme cold, ii) absence of extreme cold permits the spread of boreal species into Low Arctic tundra or ecotone.

Indicator: Winter melt days [LI33]

Phenomenon: Increasing frequency of winter melt days [LP35]

Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. IPCC concludes that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C per decade (high confidence) (Allen et al. 2018). Arctic surface air temperature has likely increased by more than twice the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming (Meredith et al. 2019). The link to anthropogenic drivers is therefore assessed as <u>certain</u> for all temperature-derived indicators, including *Winter melt days.* Frequent/long-lasting mild periods indicate a less Arctic climate (Vikhamar-Schuler et al. 2016) and increased risk of winter damage to vegetation and "rain-on-snow" events that negatively affect grazing conditions for large and small herbivores (Kausrud et al. 2008). The understanding of the significance of increasing frequency of winter melt days for the Low Arctic ecosystem is assessed as <u>good</u>. Increased frequency of winter melt days can be considered of **ecosystem significance** if, for example, i) it results in reduced grazing for reindeer with implications for fitness and/or survival, ii) it leads to suppression or absence of lemming peaks.

Indicator: Degree days [LI34]

Phenomenon: Increasing number of degree days [LP36]

Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. IPCC concludes that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C per decade (high confidence) (Allen et al. 2018). Arctic surface air temperature has likely increased by more than twice the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming (Meredith et al. 2019). The link to anthropogenic drivers is therefore assessed as <u>certain</u> for all temperature-derived indicators, including the *Degree days* (> 5°C). This indicator is closely linked to the growing season (see indicator *Growing degree days*), and the understanding of the importance of changes in this indicator for ecosystem condition is assessed as <u>good</u>, particularly for the ecosystem characteristic *Primary productivity*.

Historic records on conditions in the forest-tundra ecotone can to some degree be used as a guide for threshold values of this indicator in tundra. If current conditions in the tundra approach or correspond to historic conditions in the forest-tundra ecotone, this indicates that the tundra has shifted to a different climate regime. Such changes are considered of **ecosystem significance**.

Indicator: Growing degree days [LI35]

Phenomenon: Increasing growing degree day sum during the growing season [LP37]

Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. IPCC concludes that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C per decade (high confidence) (Allen et al. 2018). Arctic surface air temperature has likely increased by more than twice the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming (Meredith et al. 2019). The link to anthropogenic drivers is therefore assessed as <u>certain</u> for all temperature-derived indicators, including *Growing degree days.* Growing degree day sum is a common proxy of the thermal growing season (Førland et al. 2004) and the understanding of the importance of changes in this indicator for ecosystem condition via plant growth is assessed as <u>good</u> (Schmidt et al. 2018, Wipf 2010), particularly for the ecosystem characteristic *Primary productivity*.

Historic records on conditions in the forest-tundra ecotone can to some degree be used as a guide for threshold values of this indicator in tundra. If current conditions in the tundra approach or correspond to historic conditions in the forest-tundra ecotone, this indicates that the tundra has shifted to a different climate regime. Such changes will be considered of **ecosystem significance**.

Indicator: Annual mean temperature [LI36]
Phenomenon: Increasing annual temperature [LP38]
Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. IPCC concludes that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C per decade (high confidence) (Allen et al. 2018). Arctic surface air temperature has likely increased by more than twice the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming (Meredith et al. 2019). The link to anthropogenic drivers is therefore assessed as certain for all temperature-derived indicators, including *Annual mean temperature*. Annual air temperature is the key observational indicator of climate change globally and in the Arctic and is a driver of major changes in various components of the Arctic system (Box et al. 2019, IPCC 2014). Mean annual air temperature (MAAT) is one of the key determinants of Arctic permafrost (Farbrot et al. 2013).

The understanding of the ecological importance of changes in annual mean temperature is assessed as good, although the link to biotic changes via permafrost is less clear, as permafrost is sporadic (i.e. patchy with little total areal extent) in the Low Arctic region, and has been so also under the reference condition. Increased annual temperatures can be considered of **ecosystem significance** if, for example, i) they integrate effects of seasonal temperature changes that are linked to ecological processes. Increasing temperatures in the cold season may reduce energetic requirements for predators, but negatively affect mammalian herbivores, and increasing temperatures in the growing season increase plant growth. Together these effects will change the relative abundance of trophic levels. Seen in conjunction with the indicators, *January mean temperature* and *July mean temperature*, this indicator contributes towards our understanding of climate impact pathways on ecosystem characteristics.

Indicator: January mean temperature [LI37]
Phenomenon: Increasing January temperature [LP39]
Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. IPCC concludes that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C per decade (high confidence) (Allen et al. 2018). Arctic surface air temperature has likely increased by more than twice the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming (Meredith et al. 2019). The link to anthropogenic drivers is therefore assessed as certain for all temperature-derived indicators, including *January mean temperature.*

Arctic warming occurs more rapidly in the Arctic than at lower latitudes, and this difference (i.e. Arctic amplification; Serreze and Barry 2011) is more pronounced during the cold than during the warm season (Box et al. 2019). The indicator *January mean temperature* should hence be seen as an indicator of temperature during the coldest part of the year and assessed in connection with the indicators *Days with extreme cold* and *Winter melt days*, both of which have more specific and documented links to ecological effects of higher winter temperatures in the Low Arctic. The understanding of the importance of changes in winter temperatures, is assessed as good, despite less explicit links to ecological effects on the tundra ecosystem than the other two winter climate indicators *Days with extreme cold* and *Winter melt days*. These indicators should be viewed in concert. Increased January temperatures can be considered of **ecosystem significance** if, for example, they result in more frequent above-zero temperatures leading to increased icing and reduced grazing for reindeer or rodents. Change in January temperature can also impact winter thermal conditions on the ground with consequences for fine-scale vegetation patterns (Berteaux et al. 2017, Hansen et al. 2013, Niittynen et al. 2020b, Stien et al. 2012).

Indicator: July mean temperature [LI38]
Phenomenon: Increasing July temperature [LP40]
Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. IPCC concludes that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C per decade (high confidence) surface air temperature has likely increased by more than twice the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming (Meredith et al. 2019). The link to anthropogenic drivers is therefore assessed as certain for all temperature-derived indicators, including *July mean temperature.*

An average July temperature of 10°C is a commonly used proxy for climatically delineating the Arctic from the boreal, as, on a circumpolar basis, the Arctic tree lines fall largely within the zone of 10–12°C July temperature (Epstein et al. 2004). As an indicator of ecological condition of Low Arctic ecosystems, increasing July temperature beyond the variation observed during the climatic reference, indicates a degraded condition because it means that these regions will eventually support northern boreal ecosystems. The understanding of the importance of changes in this indicator is assessed as good, due to well established links between the values of this indicator and to the southern delineation of Low Arctic tundra, and to a good understanding of the role of increasing summer temperatures for plant productivity. Still, fundamental knowledge in particular about how rapidly also changes in summer temperature will affect the characteristics of the tundra ecosystem, including central trophic interaction, is missing. If current conditions in the tundra approach or correspond to historic conditions in the forest-tundra ecotone, this indicates that the tundra has shifted to a different climate regime. Such changes will be considered of **ecosystem significance**.

Indicator: Annual precipitation [LI39]
Phenomenon: Changes in annual precipitation [LP41]
Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. This link is assessed as <u>certain</u> (Bintanja and Selten 2014, Christensen et al. 2013a, Zhang et al. 2013). Increased annual precipitation is expected in the Arctic, but with major spatial variations and seasonal heterogeneity (Callaghan et al. 2011, Hanssen-Bauer et al. 2015). Increased annual precipitation will affect tundra hydrology, for example through increased paludification (Skre et al. 2002), with implications for plant growing conditions, especially the spread of thicket and forest (Crawford et al. 2003, Simard et al. 2007). The understanding of the importance of changes in the precipitation regime for Low Arctic tundra ecosystems is assessed as <u>less good</u>. Changes can be considered of **ecosystem significance** if, for example, i) they can be linked to extensive transition between vegetation types, e.g. paludification, ii) they result in deterioration of grazing conditions for large and small herbivores.

Indicator: Precipitation during growing season [LI40]
Phenomenon: Changes in precipitation during the growing season [LP42]
Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of change in this indicator is climate change. This link is assessed as <u>certain</u> (Bintanja and Selten 2014, Christensen et al. 2013a, Zhang et al. 2013). Low Arctic tundra in Norway is expected to receive increased amounts of precipitation in summer and winter (Hanssen-Bauer et al. 2015; Precipitation region 13, Varanger). The understanding of the importance of changes in precipitation patterns during the growing season for Low Arctic tundra ecosystems is assessed as <u>less good</u>. Changes can be considered of **ecosystem significance** if, for example, i) they can be linked to extensive transition between vegetation types, e.g. through improved growing conditions for thickets in tundra, ii) they result in increased presence of summer drought that affects growth and survival of trees in forest-tundra.

Indicator: Snow cover duration [LI41]
Phenomenon: Shorter season with snow cover [LP43]
Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of change in this indicator is climate change. On a local scale, grazing pressure can influence this indicator through vegetation structure (bushes/trees; te Beest et al. 2016). The links to these drivers are therefore assessed as certain. The persistence and depth of the snow cover is one of the most important factors determining tundra vegetation characteristics (Niittynen et al. 2020b, Niittynen et al. 2018, 2020a), and the understanding of the importance of changes in duration of snow cover for the tundra ecosystem is assessed as good. Changes in the duration of snow cover can be considered of **ecosystem significance** if, for example, i) snowbed—snow-free ridge gradients change, ii) they result in shrinkage of areas with snowbed vegetation.

Weather and climatic variability is driving Arctic tundra ecosystems, here illustrated by seasonal landscapes in typical Low Arctic tundra in Finnmark. Photos: G. Vie/UiT

Indicator: Basal ice [LI42]
Phenomenon: Increasing presence of basal ice/hard snow in the bottom layer [LP44]
Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

Basal ice is an indicator where data for the climate reference period is not available, and which has a complex (and partly unclear) relationship to various climate factors (interpolated values for wind, precipitation, and temperature). At present it is therefore impossible to establish modelled values for basal ice in the reference period. The most important anthropogenic driver of change in this indicator is climate change, and the links are certain. Increased presence of basal ice in the tundra indicates less stable winters/increased prevalence of "rain-on-snow" events. It affects grazing and survival of rodents in subnivean spaces, especially lemming, and may potentially affect forage availability for large herbivores (Forbes et al. 2016, Hansen et al. 2013, Hansen et al. 2019a, Kausrud et al. 2008). The understanding of the significance of increased presence of basal ice is assessed as good. Increased presence of basal ice in Low Arctic tundra can be considered of **ecosystem significance** if, for example, i) it affects the number of lemming relative to other rodents and/or the amplitude of lemming peaks, ii) it affects vital rates and population dynamics of ungulates.

Changes in the snow conditions during winter affect the vital rates and population dynamics of herbivores on the Arctic tundra. Photo: J.E. Knutsen

5.1.2 Scientific evidence base — High Arctic tundra

Indicator: Maximum vegetation productivity [HI01]
Phenomenon: Changes in maximum vegetation productivity — greening and browning [HP01]
Ecosystem characteristic: Primary productivity

Under the reference condition, maximum primary production defined for High Arctic bioclimatic subzones A-C (CAVM Team 2003, Raynolds et al. 2012) is mainly limited by temperature and moisture during the growing season (Berner et al. 2020, Elmendorf et al. 2012). Within these subzones, the indicator will vary between different types of vegetation and landscape, for example owing to topographic, edaphic and hydrological conditions. Data from field-based or remote sensing studies, on which to base reference values, are unavailable for Norwegian High Arctic regions during the climatic reference period. However, consistent change rates in indicators monitored by remote sensing, when interpreted in relation to changes in important drivers, provide indicators of deviation from a good condition (Frey et al. 2020).

The most important anthropogenic driver of changes in this indicator is climate change, acting through altered growing conditions (Berner et al. 2020, Elmendorf et al. 2015, Myers-Smith et al. 2020). Milder winters can lead to increasing prevalence of winter damage to vegetation (Bjerke et al. 2017, Bokhorst et al. 2009). Erosion caused by permafrost thawing, or grubbing damage caused by growing goose populations (Pedersen et al. 2013a), can contribute locally to lower productivity (Ravolainen et al. 2020). The link to anthropogenic drivers is assessed as <u>certain</u>, but vegetation productivity is a result of multiple drivers operating on different scales, making it still a challenge to distinguish the effects of different drivers (Ravolainen et al. 2020). Vegetation responses to drivers are far from uniform and although vegetation can and does on some occasions respond with increased growth to higher temperatures (van der Wal and Stien 2014), recent field studies (Bjorkman et al. 2020) and remote sensing studies (Berner et al. 2020, Myers-Smith et al. 2020) found no such vegetation response to higher temperatures. The understanding of the importance of changes in vegetation productivity in the High Arctic ecosystem is assessed as <u>less good</u>. Both greening and browning trends of the indicator can indicate worsened ecological condition, depending on the cause. Greening trends indicate that the system is shifting towards a more productive, and hence less Arctic state. Greening trends can be considered of **ecosystem significance** if, for example, i) increased productivity can be linked to transitions in which more productive vegetation types, possibly with greater dominance of woody plants, replace less productive vegetation types, ii) productivity over time in High Arctic areas approaches or corresponds to that of Low Arctic zones. Browning trends in the tundra may indicate vegetation damage during winter, increased grazing pressure, or erosion. Browning trends are assessed as **ecosystem significance** if, for example, i) they affect the availability of grazing for local herbivores.

Indicator: Start of growing season [HI02]
Phenomenon: Earlier start of growing season [HP02]
Ecosystem characteristic: Primary productivity

Under the reference condition, the start of the growing season (i.e. spring green-up of vegetation), is in principle determined by the climate regime during the reference period 1961–1990. Although data on climate are available from that period, the climate variables of interest lack the spatial resolution required to define snow conditions and temperatures relevant for vegetation and thus also to set reference values for the Norwegian High Arctic.

The timing of the start of the growing season, as expected under the reference condition, is in principle determined by the climate regime during the climatic reference period 1961–1990. The most important anthropogenic driver of changes in this indicator is climate change. The start of the growing season is influenced by temperature and snowmelt (Assmann et al. 2019), although sensitivity to different aspects of temperature vary between plant species, growth forms and Arctic regions (Oberbauer et al. 2013). Climate change is expected to give an earlier start of the growing season, but a shorter period of growth and flowering due to earlier senescence (Oberbauer et al. 2013, Prevey et al. 2019), owing to earlier snowmelt and higher temperatures in spring. The links to these drivers are assessed as <u>certain</u> (Assmann et al. 2019, Semenchuk et al. 2016). The timing of the start of the growing season is central to many trophic interactions (Durant et al. 2005, Høye et al. 2007), and the understanding of the importance of changes at the start of the growing season for the High Arctic tundra is assessed as <u>good</u>. Changes can be considered of **ecosystem significance** if they, for example, i) result in increased mismatch between timing of start of the growing season and critical life stages for herbivores, e.g. Svalbard rock ptarmigan breeding phenology and forage availability, ii) drive extensive changes in vegetation through a prolonged snow-free season.

In High Arctic Svalbard, the responses of vegetation to increased summer temperatures and milder winters vary across geographic scale, and both greening (increased plant biomass) and browning (increased vegetation damage) are observed. Photos: I. Eischeid/UiT (left), C. Jaspers/NPI (upper right) A. K. Balto/NPI (lower right)

Indicator: Maximum vegetation productivity versus Svalbard reindeer [HI03]
Phenomenon: Changes in the ratio of maximum vegetation productivity to Svalbard reindeer abundance [HP03]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, the abundance of Svalbard reindeer correlates with variation in plant biomass (Le Moullec et al. 2019) and exerts grazing and fertilising effects that contribute to maintaining productive tundra vegetation, e.g. by stimulating growth of grass and reducing moss biomass (van der Wal 2006, van der Wal and Brooker 2004).

The most important anthropogenic driver of changes in this indicator is climate change. The links between anthropogenic drivers and both vegetation productivity and reindeer are assessed as certain (Albon et al. 2017, van der Wal and Stien 2014). Vegetation can and does in some occasions respond with increased growth to higher temperatures in Svalbard (van der Wal and Stien 2014). At the Holarctic scale, however, this pattern is less clear (Berner et al. 2020, Bjorkman et al. 2020). Moreover, it is not equally certain how anthropogenic drivers will affect the relative biomass of plants vs. reindeer. The indicator should be assessed in relation to patterns in the individual indicators, *Maximum vegetation productivity* and *Svalbard reindeer abundance.* Shifts in the biomass ratio between vegetation productivity and ungulates can indicate worsened condition, depending on the cause. Climate change can potentially lead to increasing and decreasing reindeer populations depending on the relative impact on summer and winter grazing conditions (snow and ice conditions), and how these in sum impact reindeer populations (Albon et al. 2017, Hansen et al. 2019a, Hansen et al. 2019b). Reindeer underabundance and overabundance may potentially lead to state changes in vegetation, and changes in vegetation productivity (van der Wal 2006). However, the understanding of the importance of changes in the ratio of maximum vegetation productivity to Svalbard reindeer abundance in the High Arctic ecosystem is assessed as less good. Changes in this indicator can be considered of **ecosystem significance** if, for example, i) the shift is caused by overabundance of reindeer that negatively affects maximum vegetation productivity, ii) changes result in extensive state changes in vegetation.

Indicator: Maximum vegetation productivity versus geese [HI04]
Phenomenon: Increased biomass of geese relative to plants in the food web [HP04]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, the abundance of geese is at a level where their grazing can have local effects on vegetation (Pedersen et al. 2013a, Pedersen et al. 2013b, Speed et al. 2009), but does not contribute to consistent significant changes in plant biomass or hydrology over time in the tundra.

The most important anthropogenic drivers of change in this indicator are climate change and hunting (only for pink-footed goose; Clausen et al. 2017, Jensen et al. 2014, Jensen et al. 2016, Jensen et al. 2017, Madsen et al. 2017). Although the link between the drivers and vegetation productivity and geese is assessed as certain, it is not equally certain how anthropogenic drivers in combination affect the vegetation productivity versus geese. Therefore, the indicator should be assessed in relation to the indicators, *Maximum vegetation productivity*, *Pink-footed goose abundance* and *Barnacle goose abundance*. A shift towards a larger total number of geese (goose biomass) relative to plant productivity is expected to have a more negative impact on ecological condition than the inverse shift. Increasing abundance of geese is associated with locally reduced plant biomass and to some extent also erosion over broader areas (e.g. greater impact in dry or elevated areas;

Pedersen et al. 2013a, Pedersen et al. 2013b, Speed et al. 2009), however, influenced by seasonal changes (Anderson et al. 2016). State changes from vegetated to non-vegetated stages may occur (Ravolainen et al. 2020). The understanding of the importance of changes in this indicator is assessed as good. Shifts in relative biomass of plant growth forms versus geese can be considered of **ecosystem significance** if, for example, i) a high abundance of geese leads to increasing erosion and/or state changes from vegetated to non-vegetated ground.

Indicator: Herbivorous vertebrates versus Arctic fox [HI05]
Phenomenon: Changes in relative biomass of herbivorous vertebrates and Arctic fox [HP05]
Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, herbivorous vertebrates (reindeer and geese) are present at population levels that support viable populations of Arctic fox. Although Arctic fox abundance in a reference condition covaries with herbivore biomass (especially the availability of reindeer carcasses; Eide et al. 2012, Fuglei et al. 2003), the trophic links/covariations within terrestrial food webs are complicated by the fact that Arctic fox also frequently use marine resources, which also fluctuate (Ehrich et al. 2015, Nater et al. 2021).

The most important anthropogenic drivers of change in this indicator are climate change and hunting (Ims et al. 2013a). Although the links between these drivers and both vegetation productivity and individual species are assessed as certain, it is not equally certain how anthropogenic drivers in combination affect the relative biomass of herbivorous vertebrates and Arctic fox. The indicator should therefore be assessed in close relation to indicators for the herbivores. Shifts in the relative biomass of herbivorous vertebrates and Arctic fox can be attributed to changes in the terrestrial and the marine ecosystems, i.e. through Arctic fox feeding on supplementary marine resources (Eide et al. 2012, Nater et al. 2021) and goose nest predation by polar bears (Prop et al. 2015) and Arctic foxes (Layton-Matthews et al. 2020, Loonen et al. 1998). In addition, Arctic fox, reindeer, and pink-footed geese are all affected by hunting, although the offtake is highly variable for Arctic fox, and low for pink-footed geese and reindeer in Svalbard, but significant for pink-footed goose in the staging and wintering areas outside the Svalbard breeding grounds (Madsen et al. 2017). Overall, the understanding of the importance of changes in this indicator is assessed as less good. Changes in the relative biomass of herbivorous vertebrates and Arctic fox can be considered of **ecosystem significance** if, for example, i) they indicate that the size of the Arctic fox population does not respond (i.e. covary) with the size of herbivore population in the food web, ii) they result in strongly increased or decreased predation pressure on geese and other ground-nesting birds.

Indicator: Herbivorous vertebrates [HI06]
Phenomenon: Changes in composition of the functional group herbivorous vertebrates [HP06]
Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, the functionally disparate herbivores Svalbard reindeer, geese, and Svalbard rock ptarmigan coexist without substantial competition for resources. Reindeer and ptarmigan populations vary in parallel because they are similarly affected by variations in winter climate (Hansen et al. 2013).

The most important anthropogenic drivers of change in this indicator are climate change, farmland policy in wintering areas (for geese) and hunting. The links to these drivers are assessed as certain. Climate change, altered resource availability and quality, changes in hunting pressure and predation can alter the relative abundance and potential competition between the different herbivorous vertebrates. The assessment of this indicator emphasises comprehensive changes at group level (i.e. within a trophic level) that affect ecosystem function and represent a less Arctic condition. Particularly, focus is directed at reduced abundance of typically Arctic or endemic species and the functions these represent. Changes in composition (population sizes and demographic rates) or reduced covariation of these species can indicate a change in, or a stronger effect of, drivers or more competition/predation, depending on the ecological/climatological context. Increasing potential competition over Svalbard rock ptarmigan forage resources, due to increased impact of geese on vegetation outside the moss tundra habitats, can result in negative covariation between ptarmigan and geese (but see Pedersen et al. 2018). Overall, the understanding of the importance of changes in this indicator is assessed as less good. Changes in this indicator can be considered of **ecosystem significance** if, i) the population size of one or more species changes to a level that there are negative repercussions on the other species within the functional group.

The Arctic fox is the top predator in the terrestrial food web. In summer geese, seabirds, and ground breeding birds are common prey species. In winter, when prey are scarce, reindeer carcasses are important to Arctic fox survival and reproduction. Photos: B. Frantzen/NIBIO

Indicator: Pink-footed goose abundance [HI07]
Phenomenon: Changes in the abundance of pink-footed goose [HP07]
Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, the abundance of pink-footed goose is at a level that ensures viable populations and does not contribute to consistent changes in plant biomass over time, possibly leading to vegetation state shifts (Speed et al. 2009).

The most important anthropogenic drivers of change in this indicator are hunting (Johnson et al. 2020, Madsen et al. 2017) and climate change, which can have positive effects in terms of; 1) reproduction, as earlier start of spring will increase the availability of nesting sites (Jensen et al. 2014, Madsen et al. 2007) and increasing plant biomass will have positive effects on reproductive success, 2) improved food availability at stopover sites (Baveco et al. 2017), and 3) food quality and availability via climate-driven land-use changes (Clausen et al. 2018a, Clausen et al. 2018b). Climate change can also exert negative impact on geese through increased phenological mismatch between availability of forage and migration (Clausen and Clausen 2013), time of nesting and presence of high-quality forage for geese (Doiron et al. 2015). High availability of reindeer carcasses in winter will have a positive effect on Arctic fox reproduction and can thus increase Arctic fox predation pressure on pink-footed geese. Increased availability of reindeer carcasses probably results from a combination of increased reindeer population abundances, through natural recolonisation of former ranges and re-introductions (Le Moullec et al. 2019), and increased reindeer mortality because of changes in winter climate (i.e. amount of rain leading to basal ice) (Albon et al. 2017, Hansen et al. 2019a). Another anthropogenic driver is the hunting, which mostly occurs at the autumn stopover sites and in the overwintering areas (Madsen et al. 2017). The links to anthropogenic drivers are assessed as <u>certain</u>, even though the individual relationships acting through phenological mismatch between nesting time and forage quality and more reindeer carcasses are assessed as <u>uncertain</u>. The pink-footed goose population is at present most affected by hunting, which is a management tool to regulate the population to minimise the damage and conflicts with agriculture in winter and stopover-sites and the grazing effects on the Arctic tundra (Madsen et al. 2017).

Increasing and drastically declining populations of pink-footed geese may indicate a poor ecological condition. For instance, increasing abundance of geese may be associated with reduced plant biomass and to some extent also erosion over broader areas (e.g. greater impact in dry or elevated areas, Pedersen et al. 2013b; but see Anderson et al. 2016). State changes from vegetated to non-vegetated stages may occur (although goose distribution may expand due to population increase in combination with a warmer Arctic; see Jensen et al. 2007). In addition, the abundance and geographical expansion of pink-footed geese will depend on the timing of onset of spring (Jensen et al. 2008, Madsen et al. 2007). The indicator must therefore be assessed in close relation to the indicators *Maximum vegetation productivity versus geese* and *Start of growing season*. Overall, the understanding of the significance of changes in this indicator is assessed as <u>good</u>. Declining abundance will reduce the importance of pink-footed geese as a key species in the High Arctic ecosystem and, for example, reduce the availability of resources for the Arctic fox. Changes in the abundance of pink-footed geese can be considered of **ecosystem significance** if, for example, i) a high abundance of geese results in increasing erosion and/or state changes from vegetated to non-vegetated ground, or ii) underabundance leads to reproductive failure in Arctic fox.

Indicator: Barnacle goose abundance [HI08]
Phenomenon: Changes in the abundance of barnacle goose [HP08]
Ecosystem characteristic: Functionally important species and biophysical structures
Under the reference condition, the abundance of barnacle goose is at a level that ensures viable populations and does not contribute to consistent changes in plant biomass over time.

The most important anthropogenic driver of change in this indicator is climate change, which can have both positive and negative effects. The link to this driver is assessed as <u>certain</u>. Earlier start of spring, increasing plant biomass (Prop and Devries 1993), and declining presence of sea ice around breeding islands, which protects nesting sites against predation by foxes (Tombre, et al. 1998), have positive effects on the reproductive success of barnacle geese. Higher spring temperatures at their spring stopover sites in Norway are also suggested to be a driver for population increase (Tombre et al. 2019). Climate change can also exert a negative impact on barnacle goose through increased phenological mismatch between time of nesting and presence of high-quality forage, as has been demonstrated for snow geese (Doiron et al. 2015), and increased predation by polar bears on colonies on islands and along the coast (Prop et al. 2015). High availability of reindeer carcasses in winter has a positive effect on Arctic fox reproduction and can thus increase predation pressure on barnacle geese. The links to anthropogenic drivers are assessed as certain, even though the individual relationships acting through phenological mismatch between nesting time and forage quality and more reindeer carcasses are assessed as uncertain. Growing and drastically declining populations of barnacle geese can indicate poor ecological condition. Increasing abundance of geese is associated with reduced plant biomass over broader areas, particularly in moist habitats (van der Wal et al. 2001), and intensive goose grazing may also affect the floral abundance (Kuijper et al. 2006). The indicator must therefore be assessed in close relation to the indicator *Plant growth forms versus geese*. Overall, the understanding of the significance of changes in this indicator is assessed as good. Declining abundance will reduce the importance of barnacle goose as a key species in the High Arctic ecosystem and, for example, diminish the availability of resources for Arctic fox. Changes in the abundance of barnacle geese can be considered of **ecosystem significance** if, for example, i) growing numbers or a consistently high abundance of geese result in vegetation state changes, ii) underabundance leads to reproductive failure in Arctic fox.

Indicator: Svalbard reindeer abundance [HI09]
Phenomenon: Change in the abundance of Svalbard reindeer [HP09]
Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, the Svalbard reindeer occurs as a functionally important herbivore in viable populations that are regulated naturally by intra-specific competition over forage resources (i.e. density-dependence) and climatic variation.

The most important anthropogenic driver of changes in this indicator is climate change (Albon et al. 2017, Hansen et al. 2019a, Hansen et al. 2019b), and the link is assessed as certain. Climate change can potentially lead to both increasing and decreasing reindeer populations depending on the magnitude of the change in climate, and its relative impact on summer grazing (e.g. increased primary production) and winter grazing (snow and ice conditions) (Albon et al. 2017, Hansen et al. 2019c). Overabundance and underabundance of reindeer can contribute to poor ecological condition through the effects of grazing on the vegetation (van der Wal 2006). Underabundance can lead to shifts in vegetation towards increased moss dominance, fewer vascular plants, and lower primary production (van der Wal and Brooker 2004), and can lead to reduced reproduction in the Arctic fox (Eide et al. 2012). Overabundance can lead to state changes in vegetation towards increased dominance of grasses (van der Wal 2006), but also to overgrazing that negatively impact the forage for the reindeer itself and other herbivores, with implications for reindeer population development over time. Overall, the understanding of the significance of changes in this indicator is assessed as good. Changes in the abundance of Svalbard reindeer can be considered of **ecosystem significance** if, for example, i) increasing abundance results in state changes in vegetation that negatively affect the reindeer itself or other herbivores, ii) underabundance over time leads to reproductive failure in Arctic fox, iii) reindeer abundance shows consistent decrease over time and leads to significant extinction risk.

The functionally disparate herbivores — Svalbard reindeer, geese (here pink-footed goose and barnacle goose), and Svalbard rock ptarmigan — coexist without substantial competition for resources under the reference conditions. Reindeer and ptarmigan populations vary in parallel because they are similarly affected by variations in winter climate with reduced population growth in years with frequent of "rain-on-snow" events. Photos: T. Nordstad/NPI (upper left), N. Lecomte/Université de Moncton (lower left), G.W. Gabrielsen/NPI (upper right), Å.Ø. Pedersen/NPI (lower right)

Indicator: Svalbard reindeer mortality rate [HI10]

Phenomenon: High or increasing mortality rate of Svalbard reindeer [HP10]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, the average mortality rates over time should not lead to population decline.

The most important anthropogenic driver of changes in this indicator is climate change (Albon et al. 2017, Hansen et al. 2019a, Hansen et al. 2019b), and the link is assessed as <u>certain</u>. Svalbard reindeer mortality varies substantially from year to year, indirectly driven by winter climate acting through grazing conditions in winter and reindeer population abundance. Occasional years with extremely high mortality rates are therefore normal. Interpreting the indicator together with the indicators *Svalbard reindeer abundance, Svalbard reindeer calf rate rate* and *Maximum vegetation productivity,* and pertinent abiotic indicators, will provide a more complete assessment of the causes underlying any observed trends in the phenomenon. The understanding of the importance of changes in Svalbard reindeer mortality is assessed as <u>good</u>. Changes in the mortality rate of Svalbard reindeer can be considered of **ecosystem significance** if, for example, i) increasing or high mortality over several years leads to lasting population decline and changed demographic structure.

Indicator: Svalbard reindeer calf rate [HI11]
Phenomenon: Low or decreasing calf rate of Svalbard reindeer [HP11]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, the average calf rate within different populations should be adequate to prevent declining population numbers.

The most important anthropogenic driver of changes in this indicator is climate change (Albon et al. 2017, Hansen et al. 2019a, Hansen et al. 2019b), and the link is assessed as <u>certain</u>. Low or decreasing calf rate signals difficult living conditions for the Svalbard reindeer. Interpreting the indicator together with the indicators *Svalbard reindeer abundance, Svalbard reindeer mortality rate* and *Maximum vegetation productivity,* and pertinent abiotic indicators, will provide a more complete assessment of the causes underlying any observed trends in the phenomenon. The understanding of the importance of changes in the indicator is assessed as <u>less good</u>. Changes in the Svalbard reindeer calf rate can be considered of **ecosystem significance** if, for example, the rate is low over time or decreases consistently.

Indicator: Arctic fox abundance [HI12]
Phenomenon: Decreasing abundance of Arctic fox [HP12]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, Arctic foxes are almost omnipresent in the tundra. In Svalbard they are generalist apex predators and scavengers exploiting terrestrial and marine resources (Ehrich et al. 2015, Eide et al. 2005). Due to the lack of small mammals, such as lemmings, the Arctic fox populations are relatively stable, with moderate year-to-year variations. The fluctuations are largely determined by the availability of resources and indirectly by climate variability, whereas trapping only has local effects on fox demography/gene pool.

The most important anthropogenic driver of changes in this indicator is climate change, which can have both positive and negative effects (Eide et al. 2012, Hansen et al. 2013, Nater et al. 2021). The link to this driver is assessed as <u>certain</u>. Arctic fox is trapped locally in Svalbard, and this can have a negative effect on the population (Ehrich et al. 2012b, Fuglei et al. 2013). Changes in Arctic fox abundance can arise through changes in resource availability, owing to fewer reindeer carcasses in winter, or reduced extent of sea ice and thus less access to marine resources. Altered trapping pressure can lead to changes in the genetic and demographic structure of the population (Ehrich et al. 2012b). Arctic fox is the main vector of zoonoses in Svalbard and changes in Arctic fox density have a direct effect on the prevalence of zoonoses (Mørk et al. 2011). Climate change acts indirectly on zoonoses through expanded distribution of the introduced and alien species listed sibling vole, increasing the risk of infection of foxes with the tapeworm *Echinococcus multilocularis* (Fuglei and Ims 2008, Henttonen et al. 2001, Stien et al. 2010). Less frequent migration of Arctic fox from regions with rabies (e.g. the Russian Arctic), owing to declining sea ice, is expected to result in lower incidence of rabies (Mørk et al. 2011). Overall, the understanding of the importance of changes in this indicator is assessed as <u>less good</u>. Changes in Arctic fox abundance can be considered of **ecosystem significance** if, for example, i) there are consistent declines over time linked to climatic drivers or trapping pressure, ii) the population no longer supports sustainable trapping.

In the High Arctic tundra, Svalbard reindeer, Arctic fox, and geese are functionally important species. The reindeer is the largest herbivore and it interacts with vegetation through grazing, fertilisation and trampling. The Arctic fox is a generalist apex predator and scavenger exploiting terrestrial and marine resources. The pink-footed goose modifies the tundra landscape though grubbing, which removes plants by root and disturbs the plant and moss layer of the tundra. Photos: B. Peeters/NTNU (left), G.W. Gabrielsen/NPI (upper right), J. Dybdahl/NPI (lower right)

Indicator: Bioclimatic subzones [HI13]

Phenomenon: Decreasing total area that meets climate criteria for the High Arctic tundra zones A, B, and C [HP13]

Ecosystem characteristic: Landscape-ecological patterns

Under the reference condition, the High Arctic tundra belongs — in purely climatic terms — to bioclimatic subzones A (Arctic polar desert zone), B (Northern Arctic tundra zone), and C (Middle Arctic tundra zone), and only rarely crosses over into Low Arctic subzone D (Southern Arctic tundra zone; CAVM Team 2003, Epstein et al. 2004).

The most important anthropogenic driver of changes in this indicator is climate change. The indicator is based on average July temperatures from the Sval-Imp dataset, and increasing July temperatures will lead to a northward shift of the Arctic zones and thus to a decrease in the total area that meets climate criteria for the High Arctic subzones A (Arctic polar desert zone), B (Northern Arctic tundra zone) and C (Middle Arctic tundra zone). IPCC concludes that it is *extremely likely* that more than half of the global warming observed between 1950 and 2010 was caused by anthropogenic effects (IPCC 2014). The link to anthropogenic drivers is therefore assessed as <u>certain</u> for all temperature-derived indicators, including bioclimatic subzones. Decreasing total area that in purely climatic terms belongs to the Arctic tundra zones A, B and C is an indication of poor ecological condition because it means that, in the long-term, these regions will be unable to support High Arctic ecosystems. However, the understanding of the importance of changes in this indicator is assessed as <u>less good</u>, due to the lack of fundamental knowledge about how, and how quickly, the ongoing rapid changes in abiotic factors will affect the characteristics of the tundra ecosystem, including central trophic interactions. Changes can be considered of **ecosystem significance** if, for example, i) entire bioclimatic subzones cease to exist ("vanishing climates"; Hoffmann et al. 2019, Tang et al. 2014, Williams et al. 2007), ii) decreasing area results in increased presence/extent of Low Arctic ecosystem features (species, functions) to the detriment of High Arctic features.

Indicator: Wilderness areas [HI14]
Phenomenon: Decreasing total area of wilderness areas [HP14]

Ecosystem characteristic: Landscape-ecological patterns

Under the reference condition, High Arctic tundra areas are essentially unaffected by major technical infrastructure.

Development is the only driver of changes in this indicator. The indicator measures areas that are unaffected by (> 5 km distant from) construction of major technical infrastructure, and the link to this driver is therefore assessed as certain. Loss of wilderness areas, and the resulting fragmentation of natural habitats, can affect land use patterns and migration routes of large grazing animals (Wolfe et al. 2000), and is therefore seen as a development towards a worsened ecological condition. However, various studies demonstrate huge contrasts in terms of whether a negative effect of a technical installation can be found, and in terms of how strong that effect is (Skarin and Ahman 2014). Studies of local effects in Svalbard are non-existent. The understanding of the significance of changes in this indicator is therefore assessed as less good. This also means that, even though loss of wilderness areas must in itself be seen as a worsening of the ecological condition, it is not considered possible to set an absolute threshold for when this loss becomes critical in general terms. It will depend on the type of perturbation, how and where it is carried out relative to key habitats such as reindeer grazing and calving grounds. Loss of wilderness area can be considered of **ecosystem significance** if, for example, i) the area lost is so large that is has impact on the movement patterns of resident species, particularly the Svalbard reindeer.

Increasing July temperatures lead to a northward shift of the Arctic zones in Svalbard. This results in a decrease in the total area that meets climate criteria for the High Arctic subzones A (Arctic polar desert zone), B (Northern Arctic tundra zone) and C (Middle Arctic tundra zone). Photos: L. Hislop/NPI (left), I. Eischeid/UiT (right)

Indicator: Svalbard rock ptarmigan breeding abundance [HI15]
Phenomenon: Decreasing abundance of breeding Svalbard rock ptarmigan [HP15]
Ecosystem characteristic: Biological diversity

Under the reference condition, the endemic sub species Svalbard rock ptarmigan occurs in small, relatively stable or growing populations in suitable habitats (< 4 % of the land area in Svalbard), which locally support sustainable hunting (Fuglei et al. 2019a, Pedersen et al. 2012, Pedersen et al. 2017, Soininen et al. 2016).

Currently, the most important anthropogenic driver is climate change (Hansen et al. 2013, Marolla et al. 2021) via increasing winter temperatures. The understanding of links to these drivers has improved through recent studies (Marolla et al. 2021) and, although complex, are assessed as certain. Ptarmigan abundance can be affected negatively by several climatic and biotic drivers that act directly or indirectly, e.g. by changing grazing conditions, increasing goose populations and thus competition for important forage species, extreme weather that negatively affects reproduction and survival (more frequent "rain-on-snow" events), variable weather in spring, more frequent rain in summer, increased predation pressure from Arctic fox and increased hunting pressure (Fuglei et al. 2019a, Hansen et al. 2013, Henden et al. 2017, Marolla et al. 2021, Soininen et al. 2016). Overall, the understanding of the importance of changes in this indicator is assessed as less good. Decreasing abundance of Svalbard rock ptarmigan can be considered of **ecosystem significance** if, for example, i) the population decline is permanent, ii) the population no longer supports sustainable hunting.

Suitable habitats support small populations of the endemic sub-species Svalbard rock ptarmigan, which are hunted locally at sustainable levels. The breeding abundance of this species is the only indicator at present for the ecosystem characteristic Biological diversity in High Arctic tundra. It is recommended to include indicators of ptarmigan reproduction and plant diversity in future assessments of Arctic tundra. Photo: N. Lecomte/Université de Moncton

Indicator: Days with extreme cold [HI16]

Phenomenon: Decreasing frequency of days with extreme cold [HP16]

Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. IPCC concludes that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C per decade (high confidence) (Allen et al. 2018). Arctic surface air temperature has likely increased by more than twice the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming (Meredith et al. 2019). The link to anthropogenic drivers is therefore assessed as certain for all temperature-derived indicators (IPCC 2014), including the number of *Days with extreme cold.* Absence of extreme cold can facilitate establishment of southern invasive species (Fournier et al. 2019). The understanding of the importance of changes in the frequency of days with extreme cold is assessed as less good for the entire High Arctic ecosystem. Decreasing frequency of days with extreme cold can be considered of **ecosystem significance** if, for example, i) decreasing frequency/absence of extreme cold allows establishment/spread of Low Arctic species in High Arctic environments.

Indicator: Winter melt days [HI17]

Phenomenon: Increasing frequency of winter melt days [HP17]

Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. IPCC concludes that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C per decade (high confidence) (Allen et al. 2018). Arctic surface air temperature has likely increased by more than twice the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming (Meredith et al. 2019). The link to anthropogenic drivers is therefore assessed as certain for all temperature-derived indicators (IPCC 2014), including the number of *Winter melt days*. Increasing frequency or duration of winter melt periods indicate a development towards a less typical High Arctic climate (Vikhamar-Schuler et al. 2016) and increased risk of winter damage to vegetation and "rain-on-snow" events that negatively affect grazing conditions for large and small herbivores. The understanding of the importance of increasing frequency of winter melt days for the High Arctic ecosystem is assessed as good. Increased frequency of winter melt days can be considered of **ecosystem significance** if, for example, i) it results in reduced grazing for Svalbard reindeer, due to ice-locked tundra habitat, with implications for fitness and/or survival.

Indicator: Degree days [HI18]

Phenomenon: Increasing number of degree days [HP18]

Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. IPCC concludes that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C per decade (high confidence) (Allen et al. 2018). Arctic surface air temperature has likely increased by more than twice the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming (Meredith et al. 2019). The link to anthropogenic drivers is therefore assessed as <u>certain</u> for all temperature-derived indicators, including *Degree days*. Degree days (> 5°C) are closely linked to the growing season (see indicator *Growing degree days*), and the understanding of the importance of changes in this indicator for ecosystem condition is assessed as <u>good</u>, particularly for the ecosystem characteristic *Primary productivity*.

Historic records of conditions in more southerly tundra zones can to some degree be used as a guide for threshold values (Xu et al. 2013). If the current conditions in High Arctic tundra zones approach or correspond to historic conditions in more southerly tundra zones (possibly Low Arctic), this indicates that the tundra has shifted to a different climate regime. This is a strong indication of a future poor condition, and such changes must be considered of **ecosystem significance**.

Indicator: Growing degree days [HI19]

Phenomenon: Increasing growing degree day sum during the growing season [HP19]

Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. IPCC concludes that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C per decade (high confidence) (Allen et al. 2018). Arctic surface air temperature has likely increased by more than twice the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming (Meredith et al. 2019). The link to anthropogenic drivers is therefore assessed as <u>certain</u> for all temperature-derived indicators, including *Growing degree days*. Growing degree day sum is a common proxy of the thermal growing season (Førland et al. 2004) and the understanding of the importance of changes in this indicator for ecosystem condition via plant growth is assessed as <u>good</u> (Schmidt et al. 2018, Wipf 2010), particularly for the ecosystem characteristic *Primary productivity*.

Historic records of conditions in more southerly tundra zones can to some degree be used as a guide for threshold values (Xu et al. 2013). If the current conditions in High Arctic tundra zones approach or correspond to historic conditions in more southerly tundra zones (possibly Low Arctic), this indicates that the tundra has shifted to a different climate regime. This is a strong indication of a future poor condition, and such changes must be considered of **ecosystem significance**.

Indicator: Annual mean temperature [HI20]
Phenomenon: Increasing annual mean temperature [HP20]
Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. IPCC concludes that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at 0.2°C per decade (high confidence) (Allen et al. 2018). Arctic surface air temperature has likely increased by more than twice the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming (Meredith et al. 2019). The link to anthropogenic drivers is therefore assessed as certain for all temperature-derived indicators, including *Annual mean temperature*. The recent increase in annual mean temperature in Svalbard is the greatest observed in Europe (Nordli et al. 2014, Nordli et al. 2020) and among the most severe in the Arctic during the last three decades (Isaksen et al. 2016). Since 1991, the rate of warming at Svalbard Airport is 1.7°C/decade, which is more than twice the Arctic average (0.8°C/decade, north of 66°N) and about seven times the global average for the same period (Nordli et al. 2020). Annual air temperature is the key observational indicator of climate change both globally and in the Arctic and is a driver of major changes in various components of the Arctic system (Box et al. 2019). The understanding of the ecological importance of changes in annual mean temperature is assessed as good. Permafrost distribution at regional scales are strongly related to mean annual temperature (Farbrot et al. 2013), and changes in mean annual temperatures will hence cause biotic changes to the ecosystem both directly via warming, and indirectly via vegetation changes caused by altered permafrost conditions.

Increased annual temperatures can be considered of **ecosystem significance** if, for example, i) they integrate effects of seasonal temperature changes. Increasing temperatures in the cold season may reduce energetic requirements for predators, but negatively affect mammalian herbivores, and increasing temperatures in the growing season increase plant growth. Together these effects will change the relative abundance of trophic levels. Seen in conjunction with seasonal indicators (e.g. July temperature), this indicator contributes to our understanding of climate impact pathways on ecosystem characteristics.

Indicator: July mean temperature [HI21]
Phenomenon: Increasing July temperature [HP21]
Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition for this assessment (Ch. 2), the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. IPCC concludes that it is *extremely likely* that more than half of the global warming observed between 1950 and 2010 was caused by anthropogenic effects (IPCC 2014). The link to anthropogenic drivers is therefore assessed as certain for all temperature-derived indicators, including *July temperature*. July temperature is closely linked to growing season and plant biomass production (van der Wal and Stien 2014), and the understanding of the significance of changes in the indicator is assessed as good. Deviation beyond the variability in the reference period indicates an extreme temperature regime, i.e. outside historically normal values. Historic records of conditions in more southerly tundra zones can to some degree be used as a guide for threshold values (Xu et al. 2013). If the current conditions in Arctic tundra zones approach or correspond to historic conditions in more southerly tundra zones (possibly Low Arctic), this indicates that the tundra has shifted to a different climate regime. This is a strong indication of a future poor condition, and such changes must be considered of **ecosystem significance**.

In Svalbard, surface air temperature has increased by more than twice the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified Arctic warming. Left panel: Permafrost collapse. Right panel: Massive ground ice from "rain-on-snow" events. Photos: A. Tarroux/NINA (left), J. Kohler/NPI (right)

Indicator: Annual precipitation [HI22]
Phenomenon: Changes in annual precipitation [HP22]
Ecosystem characteristic: Abiotic factors

In the given definition of the reference condition (Ch. 2) for this assessment, the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. Human-induced warming, loss of sea ice cover (Stroeve and Notz 2018) and enhanced poleward atmospheric moisture transport (Wickström et al. 2020) are contributing to increased atmospheric moisture and increasing precipitation over Arctic land areas (AMAP 2017), including Svalbard (Førland et al. 2020). This link is assessed as certain (Bintanja and Selten 2014, Christensen et al. 2013b, Zhang et al. 2013). The Norwegian High Arctic tundra is expected to receive an increasing amount of precipitation, with a larger increase in winter than in summer (Hanssen-Bauer et al. 2019). Increased annual precipitation will affect tundra hydrology, for example through increased paludification (Skre et al. 2002). The understanding of the importance of changes in the precipitation regime for High Arctic tundra ecosystems is assessed as less good. Changes can be considered of **ecosystem significance** if, for example, i) they can be linked to extensive transition between vegetation types, such as paludification.

Indicator: Permafrost [HI23]
Phenomenon: Increasing temperature in the top 15 m of permafrost [HP23], 2) Increased thickness of the active layer [HP24]
Ecosystem characteristic: Abiotic factors
Under the reference condition, Svalbard's High Arctic tundra has continuous permafrost with a stable, low temperature, typically between -3 and -6°C (Christiansen et al. 2010).

The most important anthropogenic driver of changes in this indicator is climate change (Isaksen et al. 2007). The links between permafrost and hydrological conditions/processes in soil and vegetation are strong and fundamentally important in the High Arctic. This link is assessed as certain (AMAP 2017). Degradation of permafrost through the increase in active-layer thickness, increased permafrost temperatures and abrupt thaw processes have significant ecological implications for tundra ecosystems, greatly altering local biodiversity, plant communities, and use of habitats for particularly invertebrate (e.g. modes of soil respiration and organic matter accumulation) (e.g. Jorgenson et al. 2006, Liljedahl et al. 2016, Nitzbon et al. 2020, Vincent et al. 2017). The understanding of the importance of changes in the permafrost for High Arctic tundra ecosystems is assessed as good. Increasing permafrost temperatures can be considered of **ecosystem significance** if, for example, i) a greater degree of permafrost thaw in summer leads to decreased soil stability, cryogenic landslides including active-layer detachments and retrogressive thaw slumps, differential ground subsidence, erosion, altered hydrological conditions, or other processes that disturb and modify vegetation.

Indicator: Snow cover duration [HI24]
Phenomenon: Shorter snow season [HP25]
Ecosystem characteristic: Abiotic factors
In the given definition of the reference condition (Ch. 2) for this assessment, the reference climate is defined as a climate corresponding to the 1961–1990 normal period. This means that under the reference condition, each of the climate variables is within the range of variability observed during the period 1961–1990.

The most important anthropogenic driver of changes in this indicator is climate change. Arctic warming has direct impacts on the timing and duration of snow cover (AMAP 2017). The link to these drivers is assessed as certain. The persistence and depth of the snow cover is one of the most important factors determining tundra vegetation characteristics (Niittynen et al. 2018). Current and projected changes in snow cover duration generate a cascade of interactions and feedbacks that affect vegetation (Bokhorst et al. 2016). Thus, future biodiversity patterns in Arctic regions are highly dependent on the evolution of snow conditions (Niittynen et al. 2018). The understanding of the importance of changes in duration of snow cover for the tundra ecosystem is assessed as good. Changes in the duration of snow cover can be considered of **ecosystem significance** if, for example, i) snowbed — snow-free ridge gradients change, ii) duration changes result in shrinkage of areas with snowbed vegetation, iii) duration changes affect availability of nest sites for pink-footed geese, hence breeding propensity and population abundances for herbivores (with a cascading effect on vegetation).

6. Ecosystem characteristics

This section briefly recapitulates what describes the seven characteristics of an ecosystem under the reference condition and what roles the indicators and their associated phenomena play for the ecosystem characteristic to which they are assigned (see also Box 2). The characteristics that describe Low Arctic and High Arctic tundra under the reference condition are described in more details in the report underlying the *System for Assessment of Ecological Condition* (Nybø and Evju (ed.) 2017; kap. 4.4.4.4 og 4.4.5.5) and the interim report on indicators for Arctic tundra (Jepsen et al. 2018). Ecological condition and expected state changes (i.e. phenomena) for most of the indicators are mainly described qualitatively (see scientific evidence base Ch. 5). Similarly, at the level of ecosystem characteristics, it is only possible to give qualitative descriptions of what characterises the reference condition. Closely related indicators assigned to the same characteristic are described together (Table 6.1a, b). The description reflects the overall role the indicator/set of indicators — in its present form, based on currently available data — should play in the assessment of the ecosystem characteristic. Potential weaknesses in the set of indicators are pointed out in the assessment of the knowledge base (Ch. 7.1). Any needs for further refinement of individual indicators, in the short and long-term, are presented in Appendix 8.1 and 8.2.

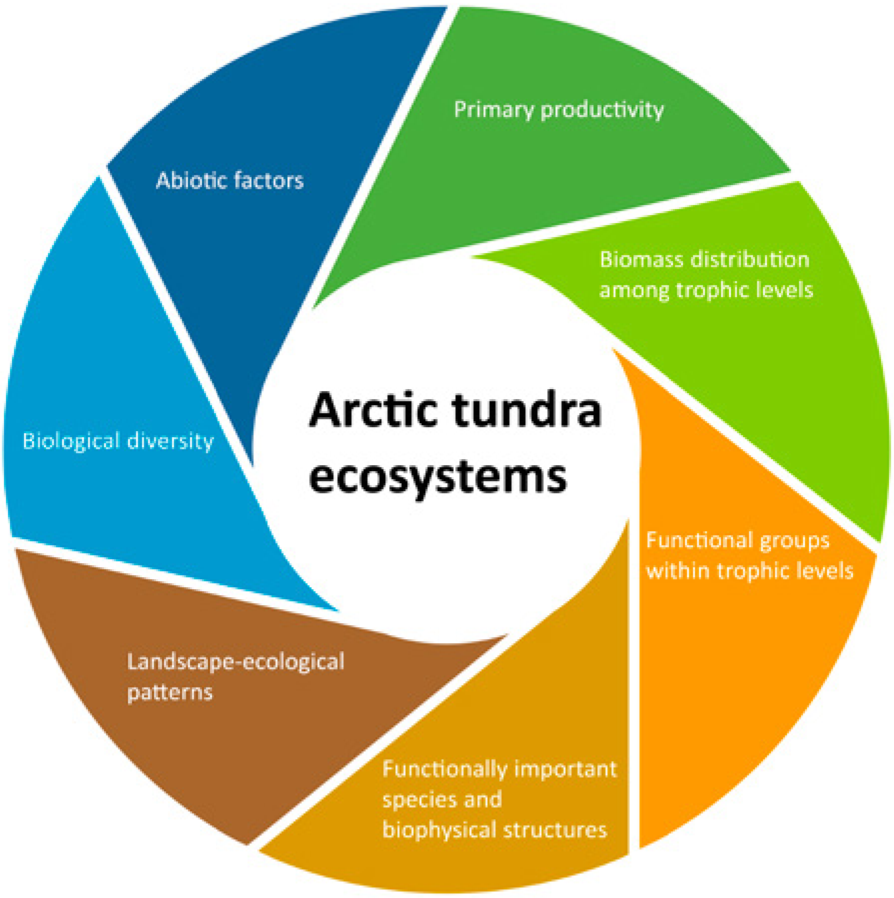


Figure 6.1. The seven ecosystem characteristics which form the basis for the *System for Assessment of Ecological Condition* in Arctic tundra ecosystems.

Table 6.1a. Description of the indicators per ecosystem characteristic in Low Arctic tundra. Each of the ecosystem characteristics is described in Box 2 and the scientific literature associated to each indicator and phenomenon in Ch. 5.1.

Ecosystem characteristic	Indicator(s)	The role of the indicator(s) in the assessment of the ecosystem characteristic
Primary productivity	Maximum vegetation productivity [LI01] Start of growing season [LI02] Plant biomass [LI03]	The three indicators for *Primary productivity* are under the reference condition mainly limited by a Low Arctic summer climate and defined by the bioclimatic subzones D–E. Partially complex vertical layers make it challenging to measure the indicators directly. Productivity (here EVI) and standing plant biomass are therefore used as a surrogate for primary production. In the assessment of the ecosystem characteristic *Primary productivity*, the indicator *Maximum vegetation productivity* serves to document regional (large-scale) trends in plant biomass/productivity (“greening”/“browning”), while the indicator *Start of growing season* serves to document phenological changes, especially in relation to trophic match/mismatch relationship between plants and herbivores. The *Plant biomass* indicator is based on detailed ground measurements in focal vegetation types (heath, meadow), and serves to nuance the satellite-based indicator *Maximum vegetation productivity*, and to document the drivers of changes between vegetation types, especially with regards to an expected shrubification in open vegetation types with a warmer Arctic.
Biomass distribution among trophic levels	Plant growth forms versus rodents [LI04] Plant growth forms versus ungulates [LI05] Rodents versus carnivorous vertebrates [LI06] Ungulates versus carnivorous vertebrates [LI07]	This set of four indicators for *Biomass distribution among trophic levels* characterises the condition of the trophic structure by focusing on two food webs that dominate the plant-based food web for Low Arctic tundra under the reference condition: 1) Plants—small rodents—carnivores, and 2) plants—ungulates—carnivores. The food webs should be considered separately as they have different natural dynamics and are expected to be exposed to different drivers and phenomena. To get interpretable indicators these are also calculated separately for the ratio between plant—herbivores and herbivore—carnivores, respectively. For the plant level, the focus is on the central tundra vegetation types (heath, meadow), and plant species/communities that are controlled by interactions with herbivores. For the carnivorous level, the focus is on specialised small rodent predators in the interaction with small rodents. Large carnivores, which in an intact ecosystem are present in the Low Arctic tundra and represent the predator level in the plants—ungulates—carnivores food web, are at present virtually absent for political reasons. For the interaction with ungulates, therefore, the focus is currently on red foxes as the most central meso/generalist predator in this ecosystem.
Functional groups within trophic levels	Plant growth forms [LI08] Herbivorous vertebrates [LI09] Carnivorous vertebrates [LI10]	In the case of the plant trophic level in the Low Arctic tundra, the reference condition is characterised by a functionally diverse composition, providing a diversity in primary production for food and biophysical structures. However, the functional composition may be shifted by direct and indirect competition among growth forms and species, potentially threatening ecosystem multifunctionality. A typical feature of Low Arctic tundra under the reference condition is that some species/species groups can be dominant within a trophic level, and thus be basis for central ecosystem functions. An expectation under climate change is that the dominance of such Arctic species/species groups decreases in favour of more boreal species. The indicator set for the ecosystem characteristic *Functional groups within trophic levels* therefore serves, particularly, to document changes in direct/indirect competition that are expected to be affected by climate change, e.g. the ratio between Arctic and more boreal species/species groups at all three trophic levels.

Table 6.1a. Continued

Ecosystem characteristic	Indicator(s)	The role of the indicator(s) in the assessment of the ecosystem characteristic
Functionally important species and biophysical structures	Thicket-forming willows [LI11]	Tall willows shrubs are a defining form of growth in the Low Arctic tundra subzone E under the reference condition, where thicket-forming willows have a distribution that is limited to only certain habitats — especially sediment surfaces around water systems where the thicket-forming willows form mosaics in meadow vegetation. The thicket-forming willows have numerous important trophic and biophysical functions. In the assessment of the ecosystem characteristic *Functionally important species and biophysical structures*, the indicator serves to document changes in the occurrence of thicket-forming willows in the central open tundra types, and condition changes from meadow to thickets (shrubification). For the time being, the data only allow this to be done on a local scale within permanent monitoring areas.
	Crowberry biomass [LI12]	The crowberry (*Empetrum nigrum*) is a dominant plant species in the Low Arctic tundra in Finnmark. Crowberry dominance is representative of nutrient-poor, dry heath vegetation under the reference condition. With substantial chemical properties that reduce the primary and secondary production and species diversity of plants, an increased dominance and spread of crowberry to more nutrient-rich areas with climate change result in a deviation from the reference condition. In the assessment of the ecosystem characteristic *Functionally important species and biophysical structures*, the indicator serves to document changes in the occurrence of crowberry in the open tundra types such as heath and meadow.
	Mountain birch in forest-tundra [LI13]	Multi-stemmed mountain birch is the defining growth form for the forest-tundra under the reference condition with several important trophic and biophysical functions. In the assessment of the ecosystem characteristic *Functionally important species and biophysical structures*, the indicator serves to document changes in density and recruitment of mountain birch in the tree-boundary ecotone, with a special focus on state changes driven by insect outbreaks.
	Lemming abundance [LI14]	The lemming cycle is the most important pulse in the food web of the focal tundra ecosystem under the reference condition, and the indicator serves to document changes in the aspects of lemming dynamics (period, amplitude, synchrony) that affect both higher and lower trophic levels the most. Seasonal changes (spring and autumn) in these aspects are also expected to be important.
	Ptarmigan density [LI15]	Ptarmigan populations under the reference condition have a sufficiently high abundance to support Arctic ptarmigan predator-specialists, such as gyrfalcon, as well as important ecosystem services (ptarmigan hunting). In the assessment of the ecosystem characteristic *Functionally important species and biophysical structures*, the indicator serves to document changes in the aspects of the ptarmigan dynamics (period, amplitude, synchrony) that affect higher trophic levels the most.
	Geometrid moth outbreaks [LI16]	Moth outbreaks are the main biotic driver of spatially extensive mortality of mountain birch in the forest-tundra ecotone. In the assessment of the ecosystem characteristic *Functionally important species and biophysical structures*, the indicator serves to document major changes in the disturbance regime of the ecotone. The indicator also documents spread of outbreaks from the ecotone to thicket-forming willows in the tundra, and therefore also considers changes in the disturbance regime of thicket-forming willows.

Table 6.1a. Continued

Ecosystem characteristic	Indicator(s)	The role of the indicator(s) in the assessment of the ecosystem characteristic
Functionally important species and biophysical structures (continued)	Semi-domestic reindeer abundance [LI17]	Reindeer are the functionally most important large herbivores of the Low Arctic tundra and forest-tundra ecotone under the reference condition. Reindeer help to maintain the tundra's characteristic open vegetation types, by counteracting shrubification and expansion of the forest-tundra. They constitute the most significant ecosystem service for reindeer husbandry and the Sami population in eastern Finnmark. This set of three indicators, based on official statistics, serves to document changes in the condition of the reindeer population in relation to the grazing grounds, climate and management.
	Semi-domestic reindeer calf body mass [LI18]	
	Semi-domestic reindeer calf rate [LI19]	
	Red fox camera index [LI20]	Low Arctic tundra under the reference condition constitutes only a marginal habitat for red foxes, which is an effective boreal meso/generalist predator. Increasing populations are expected to have significant effects on Arctic species of ground-nesting birds and become a dominant competitor to the Arctic fox. In the assessment of the ecosystem characteristic *Functionally important species and biophysical structures*, the indicator serves to document the expected increase in the occurrence of red foxes along climatic gradients and to document the effect of ongoing management actions aimed at controlling this expanding generalist predator and re-establishing the Arctic fox population.
	Large predators [LI21]	Large predators can have significant impact on structure, functioning, and dynamics of ecosystems. In intact Low Arctic Norwegian tundra, viable populations of wolves and wolverines are expected. The lack of wolves and low abundance of wolverines is the result of a management strategy that prioritises semi-domesticated reindeer and domestic sheep over these large predators. The indicator *Large predators* documents changes in these red-listed species.
Landscape-ecological patterns	Snowbed encroachment [LI22]	Snowbeds are a climatically sensitive and sparsely distributed vegetation type that constitute an important habitat for lemmings and summer grazing for reindeer under the reference condition. The current data do not allow an indicator of the prevalence of snowbeds on neither a local nor a regional scale, but detailed monitoring data allow to quantify changes in the degree of shrubification by woody plants in snowbeds within permanent monitoring areas. In the assessment of the ecosystem characteristic *Landscape-ecological patterns*, this indicator will serve to document this central change in relation to climate, small rodent dynamics, and plant biomass available for reindeer.
	Bioclimatic subzones [LI23]	The circumpolar bioclimatic subzones D and E are defining for the Low Arctic ecosystem under the reference condition. For the ecosystem characteristic *Landscape-ecological patterns*, the change in the geographical distribution of these subzones over time is an overall indicator of the future (potential) ecological condition of the ecosystem.

Table 6.1a. Continued

Ecosystem characteristic	Indicator(s)	The role of the indicator(s) in the assessment of the ecosystem characteristic
Landscape-ecological patterns (continued)	Wilderness areas [LI24]	The Low Arctic tundra under the reference condition is only marginally affected by major technical infrastructure. The indicator *Wilderness areas* is a simple calculation, based on official statistics, of how much of the ecosystem's area is unaffected by major technical infrastructure. The indicator thus has its greatest relevance in ecosystems that are strongly affected by human development and major technical infrastructure. Area loss and habitat fragmentation are key landscape-ecological patterns, and changes in these due to major technical infrastructure are well documented by this indicator.
Biological diversity	Plant communities [LI25]	The composition and species richness of plant communities are key to the functioning of an ecosystem. Under the reference condition, the Low Arctic plant community is dominated by Arctic–alpine species, including species from a set of functional groups that characterise open tundra habitats. In the assessment of the ecosystem characteristic *Biological diversity*, this indicator serves to document changes in the ratio between the richness and abundance of typical Arctic tundra species and species associated to the boreal and nemoral biomes. It also seeks to address the ratio between the richness and abundance of herbaceous to woody species along with finer functional groupings.
	Arctic fox abundance [LI26] Arctic fox litter size [LI27] Arctic fox camera index [LI28] Snowy owl abundance [LI29] Snowy owl fecundity [LI30]	Arctic foxes and snowy owls are characteristic Arctic species at the top of the food web when the ecosystem is under the reference condition. Viable population sizes resulting from sufficient production (number of litters and litter sizes) depend on regular lemming cycles and for Arctic foxes also on a moderate level of interspecific competition from expanding boreal red foxes. The Arctic fox has been chosen as climate change flagship species by IUCN. In the Low Arctic Norwegian tundra, the species has nearly gone extinct and is at present subject to intensive management actions to re-establish the population. In the assessment of the ecosystem characteristic *Biological diversity*, both Arctic foxes and snowy owls are key indicators of "trophic collapse" due to changes in lower trophic levels (e.g. altered lemming dynamics) or due to competition and predation from invasive boreal species (red fox and golden eagle). The Arctic fox indicators serve to document the effects of ongoing management actions.
	Bird communities [LI31]	The composition and species richness of bird communities are key indicators of the condition of an ecosystem. Under the reference condition, the Low Arctic bird community is dominated by species that characterise open tundra habitats. In the assessment of the ecosystem characteristic *Biological diversity*, this indicator serves to document changes in the occurrence and ratio between typical Arctic and more boreal species associated with riparian tundra habitats and the forest-tundra
Abiotic factors	Days with extreme cold [LI32] Winter melt days [LI33] January mean temperature [LI37]	For the ecosystem characteristic *Abiotic factors* in Arctic tundra, it is the climatic conditions that are fundamental for the structure, functioning, productivity and dynamics of ecosystems. This set of indicators serves to document changes in key characteristics of the winter climate relative to the reference period 1961–1990, in the form of a general indicator of mid-winter temperature, and two specific indicators linked to boreal species establishment/occurrence of insect outbreaks (*Days with extreme cold*) and risk of basal ice and winter damage to the vegetation (*Winter melt days*).

Table 6.1a. Continued

Ecosystem characteristic	Indicator(s)	The role of the indicator(s) in the assessment of the ecosystem characteristic
Abiotic factors (continued)	Degree days [LI34]	This set of indicators serves to document changes in key characteristics of the summer climate relative to the reference period 1961–1990. July temperature is defining for the tundra's bioclimatic subzones and related to the location of the tree line. The number of degree days (days > 5°C), as well as the growing degree days (cumulative sum of degrees > 5°C), document the growth conditions throughout the growing season.
	Growing degree days [LI35]	
	July mean temperature [LI38]	
	Annual mean temperature [LI36]	This indicator serves to document changes in ambient temperature relative to the reference period 1961–1990. Annual air temperature is the key observational indicator of climate change in the Arctic and is a driver of major changes in various components of the Arctic system. It contributes to our understanding of climate impact pathways on ecosystem characteristics.
	Annual precipitation [LI39]	This set of indicators serves to document changes in key attributes of the precipitation relative to the reference period 1961–1990. Increased precipitation can change the hydrology of the tundra and affect the depth and duration of the snow cover.
	Precipitation during growing season [LI40]	
	Snow cover duration [LI41]	This set of indicators serves to document changes in key properties of the snow cover relative to the reference period 1961–1990. Under the reference condition, the typical duration, depth, and vertical structure of the snow cover constitute an important niche dimension for focal Arctic species and habitats, such as small rodents and snowbeds. Basal ice, due to mild winter weather and "rain–on–snow" events, results in poorer living conditions for small rodents and ungulates, which in turn can have substantial effects on their abundance and dynamics. Satellite and model-based data on basal ice are currently not of sufficient quality to estimate the extent of basal ice, neither on a regional nor local scale. An indicator of basal ice, based on field measurements, is crucial for interpreting population fluctuations in small rodents.
	Basal ice [LI42]	

Table 6.1b. Description of the indicators per ecosystem characteristic in High Arctic tundra. Each of the ecosystem characteristics is described in Box 2 and the scientific literature associated to each indicator and phenomenon in Ch. 5.2.

Ecosystem characteristic	Indicator(s)	The role of the indicator in the assessment of the ecosystem characteristic
Primary productivity	Maximum vegetation productivity [HI01] Start of growing season [HI02]	The two indicators for *Primary productivity* are under the reference condition mainly limited by a High Arctic summer climate and defined by the bioclimatic subzones A–C. Partially complex vertical layers make it challenging to measure the indicators directly. Productivity (here EVI) are therefore used as a surrogate for primary production. In the evaluation of the attribute *Primary productivity,* the indicator *Maximum productivity* serves to document regional (large scale) trends in plant biomass/productivity ("greening"/"browning"), while the indicator *Start of growing season* serves to document phenological changes, especially in relation to trophic match/mismatch relationship between plants and herbivores.
Biomass between trophic levels	Maximum vegetation productivity versus Svalbard reindeer [HI03] Maximum vegetation productivity versus geese [HI04] Herbivorous vertebrates versus Arctic fox [HI05]	This set of three indicators serves to document trophic structure with the focus on the two food webs dominating the plant-based food web for High Arctic tundra under the reference condition: i) plants—geese—Arctic fox, and ii) plants—reindeer—Arctic fox. The two food webs should be evaluated separately because they are expected to have different dynamic and to be exposed to different drivers and phenomenon. To be able to interpret this indicator, we calculate separately the relationship between plants—herbivores and herbivores—Arctic fox, respectively. Due to lack of time-series for ground measurements on plant growth forms, the satellite-based indicator *Maximum vegetation productivity* serves as a substitute for regional scale plant biomass.
Functional groups within trophic levels	Herbivorous vertebrates [HI06]	A typical condition for High Arctic tundra under the reference condition is that some endemic species/species groups may have completely dominant abundance within a trophic level, and thereby be premises for central ecosystem functions. One expectation under climate change is that the dominance of such species/species groups decreases for the benefit of species belonging to southern ecosystems (Low Arctic or boreal). The set of indicators for the *Functional groups within trophic levels* therefore serves specifically to document changes in direct/indirect competition relationships that are expected to be affected by climate change. The database for High Arctic tundra does not allow for an indicator for functional groups at the plant level. Since the predator level is limited to Arctic fox, this characteristic can only be evaluated on the level of herbivores.
Functionally important species and biophysical structures	Pink-footed goose abundance [HI07] Barnacle goose abundance [HI08]	The pink-footed geese and the barnacle geese are functional important herbivores in Svalbard, as they have structural effects on the vegetation, and are important food resource species for the Arctic fox. The indicator set for geese serves to document changes in the goose populations regarding drivers, climate and management in the non-breeding season on autumn staging, wintering and spring staging areas, that may lead to overabundance or underabundance with consequences for vegetation and trophic dynamics.

Table 6.1b. Continued

Ecosystem characteristic	Indicator(s)	The role of the indicator in the assessment of the ecosystem characteristic
Functionally important species and biophysical structures (continued)	Svalbard reindeer abundance [HI09]	Svalbard reindeer is an endemic subspecies and the only large herbivore in Svalbard. Under the reference condition the Svalbard reindeer is functionally important through grazing effects on the vegetation and as food resources for the Arctic fox. The Svalbard reindeer is annually harvested. The set of indicators serves to document changes in the condition of the Svalbard reindeer population in relation to the grazing basis, climate and management.
	Svalbard reindeer mortality rate [HI10]	
	Svalbard reindeer calf rate [HI11]	
	Arctic fox abundance [HI12]	The Arctic fox is the only functionally important predator in the Svalbard tundra ecosystem. Under the reference condition the Arctic fox occurs in relatively stable populations with moderate year-to-year variations mainly due to food resource availability linked to indirect climate variation, with a potential regulating effect on ground breeding birds. The species is harvested on an annual basis, is the main vector for the rabies virus and the determinant host of the tape worm *Echinococcus multilocularis*, attributed to the introduced and alien sibling vole. The indicator serves to document changes in the size of the breeding population in the monitoring areas.
Landscape-ecological patterns	Bioclimatic subzones [HI13]	The circumpolar bioclimatic subzones A–C are defining for the High Arctic ecosystem under the reference condition. For the characteristic *Landscape-ecological patterns*, the change in the geographical distribution of these subzones is over time an overall indicator on the future (potential) ecological condition of the ecosystem.
	Wilderness areas [HI14]	The High Arctic tundra under the reference condition is only marginally affected by major technical infrastructure. The indicator *Wilderness areas* is a simple calculation, based on official statistics, of how much of the ecosystem's area is unaffected by major technical infrastructure. The indicator, thus, has its greatest relevance in ecosystems that are strongly affected by human development and major technical infrastructure. Area loss and habitat fragmentation are key landscape-ecological patterns, and changes in these due to major technical infrastructure are well documented by this indicator.
Biological diversity	Svalbard rock ptarmigan breeding abundance [HI15]	Svalbard rock ptarmigan is an endemic subspecies in Svalbard, which under the reference condition occurs in low, relatively stable populations. The species is annually harvested. The species is expected to be specifically exposed to climate change due to a limited food niche with the possibility for phenological mismatch with increasing temperatures. The indicator serves to document changes in the population density related to climate and management.

Table 6.1b. Continued

Ecosystem characteristic	Indicator(s)	The role of the indicator in the assessment of the ecosystem characteristic
Abiotic factors	Days with extreme cold [HI16] Winter melt days [HI17]	For the ecosystem characteristic *Abiotic factors* in Arctic tundra, the climatic conditions are fundamental for the structure, functioning, productivity, and dynamics of the ecosystem. This set of indicators serves to document changes in key characteristics of the winter climate relative to the reference period 1961–1990. The occurrence of days with extreme cold restricts the distribution of boreal species into the tundra and the occurrence of insect outbreaks in the forest-tundra. Winter melt days increase the chance of basal ice and winter damage to the vegetation.
	Degree days [HI18] Growing degree days [HI19] July mean temperature [HI21]	This set of indicators serves to document changes in key characteristics of the summer climate relative to the reference period 1961–1990. July temperature is defining for the tundra's bioclimatic subzones and related to the location of the tree line. The number of degree days (days > 5°C), as well as the growing degree days (cumulative sum of degrees > 5°C) document the growth conditions throughout the growing season.
	Annual mean temperature [HI20]	This indicator serves to document changes in ambient temperature relative to the reference period 1961–1990. Annual air temperature is the key observational indicator of climate change in the Arctic and is a driver of major changes in various components of the Arctic system. It contributes towards our understanding of climate impact pathways on ecosystem characteristics.
	Annual precipitation [HI22]	This indicator serves to document changes in central attributes of the precipitation climate/hydrology related to the reference period of 1961–1990. Increased *Annual precipitation* may change the hydrology of the tundra and affect the snow cover depth/duration.
	Permafrost [HI23]	High Arctic tundra under the reference condition has continuous, cold permafrost with limited summer thawing and a relatively shallow active layer. In evaluating the characteristic *Abiotic factors* in the High Arctic, changes in the permafrost temperature and the depth of the active layer are central for hydrological conditions, earth processes/stability and vegetation.
	Snow cover duration [HI24]	This indicator serves to document changes in the *Snow cover duration* in relation to the reference period of 1961–1990, which together with the snow cover depth and vertical structure, determine the living environments for central Arctic species and nature types. For a High Arctic ecosystem under the reference condition, the typical snow cover duration is an important environmental dimension for typical vegetation types/gradients by impacting plant phenology, hydrology, and the length of the growing season.

7. Assessments

The overall assessment comprises three subsections. Section 7.1 presents the assessment of the overall knowledge base, from the level of individual datasets to the level of ecosystem characteristics. Section 7.2 presents the assessment of the validity of the phenomena being used, and the evidence for whether each phenomenon has occurred. Both these sections form the basis for the overall assessment (Section 7.3) of the ecological condition of each ecosystem characteristics (based on their indicators and associated phenomena) and of the ecosystem as a whole (based on the condition of their characteristics).

7.1 Assessment of the knowledge base

The overall assessment of the knowledge base is presented in tabular form (Table 7.1a Low Arctic tundra and Table 7.1b High Arctic tundra). In accordance with PAEC, the knowledge base is assessed at three levels: *Data level*, *indicator level,* and *ecosystem characteristic level*.

1. At a *data level*, we summarise the spatial (SR) and temporal (TR) representativity of the datasets for each individual indicator.
   a. The spatial representativity (*SR*) of *each dataset* relative to the target ecosystem (Ch. 3) is determined by the sampling design employed (design-based, model-based, no design). A design-based sampling is evaluated based on three criteria: 1) whether or not the entire population has the possibility of being included in the sampling (*SRd1*), 2) whether or not sampling is based on randomisation (*SRd2*), and 3) whether or not there is a known probability of including each sampling unit (*SRd3*). A model-based sampling (*SRm*) is evaluated based on just one criterium; whether or not sampling is based on a model (i.e. a sampling design) that is relevant for the indicator or phenomenon in question.
   b. The temporal representativity (*TR*) of *each dataset* relative to any temporally defined reference condition. A temporally defined reference condition includes explicit definitions (e.g. the reference condition equals the condition of the ecosystem at a particular point in time), and implicit definitions (e.g. the reference condition equals the condition of the ecosystem in, for instance, a preindustrial climate). Temporal representativity is evaluated based on two criteria: 1) With respect to years (*TRyr*; the length of the time series relative to relevant dynamics and any temporally defined reference conditions), and 2) with respect to seasonality (*TRse*; whether or not relevant seasonality is taken into account in the sampling or not).
2. At an *indicator level* we assess the indicator's total data coverage based on the overall assessment of spatial (SRtotal) and temporal (TRtotal) representativity of each dataset included.
3. At an *ecosystem characteristic level,* we assess indicator coverage for the entire *characteristic*.

This reflects the degree to which the set of indicators on which the assessment is based has sufficient coverage and relevance for assessment of the condition of the ecosystem characteristic. All assessments are assigned to clearly defined colour-coded categories (Fig. 7.1) as specified in the technical protocol (Jepsen et al. 2020). Each individual assessment is justified in an endnote, which can be found in Appendix 8.3.

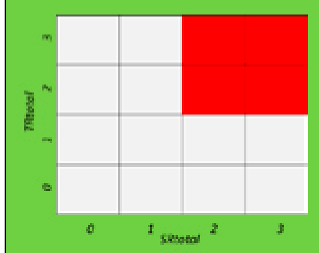
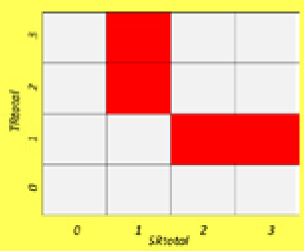
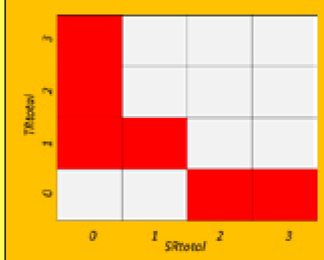
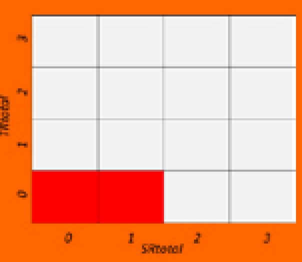
		Categories			
Spatial representativity (SR)	SRd1	**<u>Fulfilled:</u>** Design-based sampling where the entire sampling population has a possibility of being included.		**<u>Not fulfilled:</u>** Design-based sampling where only a SUBSET of the sampling population has a possibility of being included.	
	SRd2	**<u>Fulfilled:</u>** Design-based sampling based on randomisation.		**<u>Not fulfilled:</u>** Design-based sampling NOT based on randomisation.	
	SRd3	**<u>Fulfilled:</u>** Design-based sampling, with known probability of including each sampling unit.		**<u>Not fulfilled:</u>** Design-based sampling, with UNKNOWN probability of including each sampling unit.	
	SRm	**<u>Fulfilled:</u>** Model-based sampling based on a model that is relevant for the indicator and the phenomenon in question.		**<u>Not fulfilled:</u>** Model-based sampling based on a model that is NOT relevant for the indicator and the phenomenon in question.	
	SRtotal	**<u>Category 3:</u>** *SRm* fulfilled with an adequate sample size OR *SRd1-SRd3* all fulfilled.	**<u>Category 2:</u>** *SRm* fulfilled with a limited sample size OR two of *SRd1-SRd3* fulfilled.	**<u>Category 1:</u>** *SRm* not fulfilled, one of *SRd1-SRd3* fulfilled.	**<u>Category 0:</u>** *SRm* not fulfilled, none of *SRd1-SRd3* fulfilled.
Temporal representativity (TR)	TRyr	**<u>Adequate:</u>** A long time series relative to relevant dynamics. In case of a temporally defined reference condition, the time series is partly or fully overlapping with the reference period.	**<u>Partially adequate:</u>** A long time series relative to relevant dynamics. In case of a temporally defined reference condition, the time series is NOT overlapping with the reference period.		**<u>Inadequate:</u>** A short time series relative to relevant dynamics.
	TRse	**<u>Adequate:</u>** Seasonal variability is relevant and taken into account in the sampling OR seasonal variability is not relevant.		**<u>Inadequate:</u>** Seasonal variability is relevant, but not, or to a very limited degree taken into account in the sampling.	
	TRtotal	**<u>Category 3:</u>** Both *TRyr* and *TRse* are Adequate.	**<u>Category 2:</u>** *TRyr* Adequate and *TRse* Inadequate OR *TRyr* Partially adequate and *TRse* Adequate.	**<u>Category 1:</u>** *TRyr* Inadequate and *TRse* Adequate OR *TRyr* Partially adequate and *TRse* Inadequate.	**<u>Category 0:</u>** Both *TRyr* and *TRse* Inadequate.
Data coverage	DC	**<u>Very good:</u>** 	**<u>Good:</u>** 	**<u>Intermediate:</u>** 	**<u>Poor:</u>** 
Indicator coverage	IC	**<u>Adequate:</u>** The set of indicators represents the major aspects of the ecosystem characteristic with no obvious shortcomings.	**<u>Partially adequate:</u>** The set of indicators has certain shortcomings which might limit our ability to assess the condition of the ecosystem characteristic.		**<u>Inadequate:</u>** The set of indicators has severe shortcomings which will definitely limit our ability to assess the condition of the ecosystem characteristic.

Figure 7.1. Summary of the assessment criteria and colour coding for the knowledge base used in PAEC.

Table 7.1a. Assessment of the knowledge base for the datasets, indicators, and ecosystem characteristics for Low Arctic tundra. For content of each column, see Fig. 7.1. Endnotes with justification for the assessment are listed in Appendix 8.3.

DATA									INDICATOR	ECOSYSTEM CHARACTERISTIC
Dataset ID	Spatial representativity (SR)					Temporal representativity (TR)			Data coverage	Indicator coverage
	SRd1	SRd2	SRd3	SRm	**SRtotal**	TRyr	TRse	**TRtotal**	DC	IC
LD01	1	2	3	4	5	6	7	8	[9] Maximum vegetation productivity [LI01]	[10] Primary productivity
LD01	1	2	3	4	5	6	7	8	[9] Start of growing season [LI02]	
LD02	11	12	13	14	15	16	17	18	[19] Plant biomass [LI03]	
LD02	11	12	13	14	15	16	17	18	[20] Plant growth forms versus rodents [LI04]	[21] Distribution of biomass between trophic levels
LD04	22	23	24	25	26	27	28	29		
LD02	11	12	13	14	15	16	17	18	[30] Plant growth forms versus ungulates [LI05]	
LD06	31	32	33	34	35	36	37	38		
LD04	22	23	24	25	26	27	28	29	[39] Rodents versus carnivorous vertebrates [LI06]	
LD10	40	41	42	43	44	45	46	47		
LD06	31	32	33	34	35	36	37	38	[48] Ungulates versus carnivorous vertebrates [LI07]	
LD09	49	50	51	52	53	54	55	56		
LD02	11	12	13	14	15	16	17	18	[57] Plant growth forms [LI08]	[58] Functional groups within trophic levels
LD05	22	23	24	25	26	27	28	29	[59] Herbivorous vertebrates [LI09]	
LD06	31	32	33	34	35	36	37	38		
LD07	60	61	62	63	64	65	66	67		
LD11	68	69	70	71	72	73	74	75		
LD09	76	77	78	79	80	81	82	83	[84] Carnivorous vertebrates [LI10]	
LD10	40	41	42	43	44	45	46	47		
LD09	49	50	51	52	53	54	55	56		

Table 7.1a. Continued

DATA									INDICATOR	ECOSYSTEM CHARACTERISTIC
Dataset ID	**Spatial representativity (SR)**					**Temporal representativity (TR)**			**Data coverage**	**Indicator coverage**
	SRd1	SRd2	SRd3	SRm	**SRtotal**	TRyr	TRse	**TRtotal**	**DC**	**IC**
LD02	85	86	87	88	89	90	91	92	[93] Thicket-forming willows [LI11]	[94] Functionally important species and biophysical structures
LD02	11	12	13	14	15	16	17	18	[95] Crowberry biomass [LI12]	
LD15	96	97	98	99	100	101	102	103	[104] Mountain birch in forest-tundra [LI13]	
LD05	22	23	24	25	26	27	28	29	[105] Lemming abundance [LI14]	
LD11	68	69	70	71	72	73	74	75	[106] Ptarmigan density [LI15]	
LD12	107	108	109	110	111	112	113	114		
LD14	115	116	117	118	119	120	121	122	[123] Geometrid moth outbreaks [LI16]	
LD15	124	125	126	127	128	129	130	131		
LD06	31	32	33	34	35	36	37	38	[132] Semi-domestic reindeer abundance [LI17]	
LD06	133	134	135	136	137	138	139	140	[141] Semi-domestic reindeer calf body mass [LI18]	
LD06	116	117	118	119	120	121	122	123	[142] Semi-domestic reindeer calf rate [LI19]	
LD09	49	50	51	52	53	54	55	56	[143] Red fox camera index [LI20]	
LD18	144	145	146	147	148	149	150	151	[152] Large predators [LI21]	
LD03	11	12	13	14	15	16	17	18	[153] Snowbed encroachment [LI22]	[154] Landscape-ecological patterns
LD19, LD20	155	156	157	158	159	160	161	162	[163] Bioclimatic subzones [LI23]	
LD16	164	165	166	167	168	169	170	171	[172] Wilderness area [LI24]	

Table 7.1a. Continued

DATA									INDICATOR	ECOSYSTEM CHARACTERISTIC
Dataset ID	Spatial representativity (SR)					Temporal representativity (TR)			Data coverage	Indicator coverage
	SRd1	SRd2	SRd3	SRm	**SRtotal**	TRyr	TRse	**TRtotal**	DC	IC
LD02	173	174	175	176	177	178	179	180	[181] Plant communities [LI25]	[182] Biological diversity
LD08	183	184	185	186	187	188	189	190	[191] Arctic fox abundance [LI26]	
LD08	174	175	176	177	178	179	180	181	[192] Arctic fox litter size [LI27]	
LD09	76	77	78	79	80	81	82	83	[193] Arctic fox camera index [LI28]	
LD10	40	41	42	43	44	45	46	47	[194] Snowy owl abundance [LI29]	
LD10	40	41	42	43	44	45	46	47	[195] Snowy owl fecundity [LI30]	
LD17	196	197	198	199	200	201	202	203	[204] Bird communities [LI31]	
LD19	205	206	207	208	209	210	211	212	[213] Days with extreme cold [LI32]	[214] Abiotic factors
LD19	205	206	207	208	209	210	211	212	[213] Winter melt days [LI33]	
LD19	205	206	207	208	209	210	211	212	[213] Degree days [LI34]	
LD19	205	206	207	208	209	210	211	212	[213] Growing degree days [LI35]	
LD19	205	206	207	208	209	210	211	212	[213] Annual mean temperature [LI36]	
LD19	205	206	207	208	209	210	211	212	[213] January mean temperature [LI37]	
LD19	205	206	207	208	209	210	211	212	[213] July mean temperature [LI38]	
LD20	205	206	207	208	209	210	211	212	[213] Annual precipitation [LI39]	
LD20	205	206	207	208	209	210	211	212	[213] Precipitation during growing season [LI40]	
LD21	205	206	207	208	209	210	211	212	[213] Snow cover duration [LI41]	
LD22	215	216	217	218	219	229	221	222	[223] Basal ice [LI42]	

Table 7.1b. Assessment of the knowledge base for the datasets, indicators, and ecosystem characteristics for High Arctic tundra. For contents of each column, see Fig. 7.1. Endnotes with justification for the assessment is listed in Appendix 8.3.

DATA									**INDICATOR**	**ECOSYSTEM CHARACTERISTIC**
Dataset ID	**Spatial representativity (SR)**					**Temporal representativity (TR)**			**Data coverage**	**Indicator coverage**
	SRd1	SRd2	SRd3	SRm	**SRtotal**	TRyr	TRse	**TRtotal**	**DC**	**IC**
HD01	224	225	226	227	228	229	230	231	[232] Maximum vegetation productivity [HI01]	[233] Primary productivity
HD01	224	225	226	227	193	229	320	231	[232] Start of growing season [HI02]	
HD01	224	225	226	227	193	229	320	231	[234] Maximum vegetation productivity versus Svalbard reindeer [HI03]	[235] Distribution of biomass between trophic levels
HD02	236	237	238	239	240	241	242	243		
HD01	224	225	226	227	193	229	320	231	[244] Maximum vegetation productivity versus geese [HI04]	
HD04	245	246	247	248	249	250	251	252		
HD05	253	254	255	256	257	258	259	260		
HD02	236	237	238	239	240	241	242	243	[261] Herbivorous vertebrate versus Arctic fox [HI05]	
HD04	245	246	247	248	249	250	251	252		
HD05	253	254	255	256	257	258	259	260		
HD06	262	263	264	265	266	267	268	269		
HD02	236	237	238	239	240	241	242	243	[270] Herbivorous vertebrates [HI06]	[271] Functional groups within trophic levels
HD04	245	246	247	248	249	250	251	252		
HD05	253	254	255	256	257	258	259	260		
HD07	272	273	274	275	276	277	278	279		

Table 7.1b. Continued

DATA									INDICATOR	ECOSYSTEM CHARACTERISTIC
Dataset ID	**Spatial representativity (SR)**					**Temporal representativity (TR)**			**Data coverage**	**Indicator coverage**
	SRd1	SRd2	SRd3	SRm	**SRtotal**	TRyr	TRse	**TRtotal**	**DC**	**IC**
HD04	245	246	247	248	249	250	251	252	[280] Pink-footed goose abundance [HI07]	[281] Functionally important species and biophysical structures
HD05	253	254	255	256	257	258	259	260	[282] Barnacle goose abundance [HI08]	
HD02	236	237	238	239	240	241	242	243	[283] Svalbard reindeer abundance [HI09]	
HD03	284	285	286	287	288	289	290	291	[292] Svalbard reindeer mortality rate [HI10]	
HD02	236	237	238	239	240	241	242	243	[293] Svalbard reindeer calf rate [HI11]	
HD06	262	263	264	265	267	268	269	270	[294] Arctic fox abundance [HI12]	
HD09, HD10	295	296	297	298	299	300	301	302	[303] Bioclimatic subzones [HI13]	[304] Landscape-ecological patterns
HD08	305	306	307	308	309	310	311	312	[313] Wilderness areas [HI14]	
HD07	272	273	274	275	276	277	278	279	[314] Svalbard rock ptarmigan breeding abundance [HI15]	[315] Biological diversity
HD09	316	317	318	319	320	321	322	323	[324] Days with extreme cold [HI16]	[325] Abiotic factors
HD09	316	317	318	319	320	321	322	323	[324] Winter melt days [HI17]	
HD09	316	317	318	319	320	321	322	323	[324] Degree days [HI18]	
HD09	316	317	318	319	320	321	322	323	[324] Growing degree days [HI19]	
HD09	316	317	318	319	320	321	322	323	[324] Annual mean temperature [HI20]	
HD09	316	317	318	319	320	321	322	323	[324] July mean temperature [HI21]	
HD10	316	317	318	319	320	321	322	323	[324] Annual precipitation [HI22]	
HD11	326	327	328	329	330	331	332	333	[334] Permafrost [HI23]	
HD12	316	317	318	319	320	321	322	323	[324] Snow cover duration [HI24]	

7.2 Assessment of the phenomena

The overall assessment of the phenomena is presented in tabular form (Table 7.2a Low Arctic tundra and Table 7.2b High Arctic tundra). The assessment consists of two parts: An assessment of the validity of each phenomenon (VP), and an assessment of the amount of evidence indicating that each phenomenon has occurred (EP). VP and EP are assessed into the categories described below (Fig. 7.2). The assessment of the phenomenon, EP, can vary in different geographic areas of the ecosystem being assessed. This can give different EP values in different areas.

Validity of phenomenon (VP)	Evidence for phenomenon (EP)
High: A CERTAIN link to relevant drivers, and a GOOD understanding of the role of the indicator in the ecosystem.	**High:** High level of evidence that the expected changes in the indicator have occurred. High (expected or observed) ecosystem significance of observed changes.
Intermediate: A LESS CERTAIN link to relevant drivers, and a GOOD understanding of the role of the indicator in the ecosystem OR a CERTAIN link to relevant drivers, and a LESS GOOD understanding of the role of the indicator in the ecosystem.	**Intermediate:** High level of evidence that the expected changes in the indicator have occurred. Limited (expected or observed) ecosystem significance of observed changes.
	Low: Low level of evidence that the expected changes in the indicator have occurred. Low or no (expected or observed) ecosystem significance of observed changes.
Low: A LESS CERTAIN link to relevant drivers, and a LESS GOOD understanding of the role of the indicator in the ecosystem.	**None:** No evidence that the expected changes in the indicator have occurred (sufficient data).
	Insufficient: No evidence that the expected changes in the indicator have occurred (insufficient data).

Figure 7.2. The criteria and colour coding used in the assessment of the phenomena (Table 7.2a, b).

Snowy owl chicks with their lemming prey, which represent two trophic levels of a Low Arctic food chain that is expected to be very vulnerable to climate change. Typical lemen habitat displayed on the lower right. Photo: R.A. Ims/UiT

Table 7.2a. Assessment of the phenomena in Low Arctic tundra. For definitions of categories and criteria, see Fig. 7.2. The assessment of the phenomenon, EP, can vary in different areas of the ecosystem being assessed and therefore two columns are presented. Details on VP is found under the phenomenon description for each indicator in section 5.1.1.

Ecosystem characteristic	Phenomenon	Indicator	Validity of phenomenon (VP)	Evidence for phenomenon (EP)		Comments EP
Primary productivity	Changes in maximum productivity — greening and browning [LP01]	Maximum vegetation productivity	High	None	Intermediate	The evidence for this phenomenon is split between none and intermediate, since the response is very heterogeneous. Some areas show significant greening (especially tundra in the east), other a significant browning (especially the part of forest-tundra ecotone that has trees), and some areas show no change.
Primary productivity	Earlier start of the growing season [LP02]	Start of growing season	High	Low	—	Earlier start of the growing season occurs locally in the tundra and in westerns parts of the forest-tundra ecotone. Over most of the area rates of changes are non-significant.
Primary productivity	Changes in standing biomass [LP03]	Plant biomass	High	Low	—	The tendency is somewhat stronger in the eastern monitoring area, coinciding with the indicator Maximum vegetation productivity.
Biomass distribution among trophic levels	Increased plant biomass in relation to rodents in the food web [LP04]	Plant growth forms versus rodents	Intermediate	None	—	—
Biomass distribution among trophic levels	Changes in the relative biomass of plant growth forms and ungulates [LP05]	Plant growth forms versus ungulates	Intermediate	Low	—	Increasing plant biomass results in an increasing abundance ratio plants:reindeer. Rate of change is positive in the monitoring areas, but only significant in the eastern area.
Biomass distribution among trophic levels	Decreasing biomass of carnivorous vertebrates relative to rodents [LP06]	Rodents versus carnivorous vertebrates	High	None	—	—
Biomass distribution among trophic levels	Changes in the relative biomass of ungulates and carnivorous vertebrates [LP07]	Ungulates versus carnivorous vertebrates	Intermediate	Intermediate	—	The ratio reindeer:red fox is decreasing due to increasing abundance of red fox.

Table 7.2a. Continued

Ecosystem characteristic	Phenomenon	Indicator	Validity of phenomenon (VP)	Evidence for phenomenon (EP)		Comments EP
Functional groups within trophic levels	Changes in the composition of plant growth forms in the plant community [LP08]	Plant growth forms	High	Low	–	Some evidence of change in composition of plant growth forms towards a higher proportion of less palatable growth forms.
Functional groups within trophic levels	Changes in the composition of functional groups within the herbivore vertebrate community [LP09]	Herbivorous vertebrates	High	None	–	–
Functional groups within trophic levels	Borealisation of the carnivorous vertebrate community [LP10]	Carnivorous vertebrates	High	Low	–	Overall tendency towards increasing borealisation. Red fox is increasing in relation to Arctic fox in control areas, being areas where red fox is not actively culled as part of the Arctic fox management. There is a tendency towards increasing proportion of rough-legged buzzard relative to long-tailed skua, caused by increasing population of rough-legged buzzard and a weak decrease in the population of the long-tailed skua.
Functionally important species and biophysical structures	Changes in abundance of thicket-forming willows in river valleys [LP11]	Thicket-forming willows	High	None	–	–
Functionally important species and biophysical structures	Increased abundance of crowberry in open vegetation types [LP12]	Crowberry biomass	High	Low	–	Abundance of crowberry is increasing, somewhat more in the eastern monitoring area.
Functionally important species and biophysical structures	Weakened recruitment after moth outbreaks [LP13]	Mountain birch in forest-tundra	Intermediate	None	–	–

Table 7.2a. Continued

Ecosystem characteristic	Phenomenon	Indicator	Validity of phenomenon (VP)	Evidence for phenomenon (EP)		Comments EP
Functionally important species and biophysical structures	Sustained reduction of forested area and/or forest density [LP14]	Mountain birch in forest-tundra	Intermediate	High	–	High degree of evidence for changes in tree density due to die off. The changes have documented impacts on other components of the ecosystem, and EP is hence assessed as High.
Functionally important species and biophysical structures	Less frequent, less distinct peaks in the lemming cycle [LP15]	Lemming abundance	High	Low	–	Evidence for irregular lemming peaks and potentially more so towards the end of the time series, but the short time series does not allow for evaluating these as of ecological significance.
Functionally important species and biophysical structures	Low and/or decreasing abundance of willow ptarmigan [LP16]	Ptarmigan density	Intermediate	Intermediate	–	The indicator is in a poor condition with low densities compared to historical references. Recent modelling has provided evidence for effects of multiple drivers, but there is still an unexplained negative trend (Henden et al. 2021a, Henden et al. 2020). Moreover, the ecological significance of condition/trend is uncertain due to lack of indicators of specialist ptarmigan predators.
Functionally important species and biophysical structures	Invasion of new moth species that establish as outbreak species in the forest-tundra ecotone [LP17]	Geometrid moth outbreaks	High	High	–	High degree of evidence from long-term monitoring that the winter moth is now established as an outbreak species in the forest-tundra ecotone causing elevated forest mortality of ecosystem significance.
Functionally important species and biophysical structures	Establishment and spread of new moth species in willow shrub tundra far from birch forest [LP18]	Geometrid moth outbreaks	Intermediate	Low	Low	Evidence that winter moths have spread to and established in coastal willow shrub beyond the current birch forest limit. No data exist to permit conclusions regarding inland shrub-tundra. At present low expected ecosystem significance of observed changes.

Table 7.2a. Continued

Ecosystem characteristic	Phenomenon	Indicator	Validity of phenomenon (VP)	Evidence for phenomenon (EP)		Comments EP
Functionally important species and biophysical structures	Change in abundance of semi-domestic reindeer [LP19]	Semi-domestic reindeer abundance	High	Low	–	Abundance of semi-domesticated reindeer is very variable over time and the degree of evidence is fully dependent on which time period is evaluated. Over the whole time period the population is increasing in the eastern district on Varanger Peninsula, but unchanged in the western district. After the climatic reference period (i.e. 1991–present) there has been an increase in both districts. For the indicator semi-domesticated reindeer the conclusion is therefore that there is low evidence for a change towards increasing abundance of semi-domesticated reindeer.
Functionally important species and biophysical structures	Low or decreasing semi-domestic reindeer calf body mass [LP20]	Semi-domestic reindeer calf body mass	High	None	–	–
Functionally important species and biophysical structures	Low or decreasing semi-domestic reindeer calf rate [LP21]	Semi-domestic reindeer calf rate	High	None	–	–
Functionally important species and biophysical structures	Increased or high proportion of days with red fox captures by camera traps [LP22]	Red fox camera index	High	Low	–	Number of days with red fox captured by camera traps has increased in both the areas with management actions and in control areas. Numbers are largest in the control areal, i.e. in areas where red foxes are not culled as part of the Arctic fox management, but the increase over 2005–2020 was stronger in the management area.
Functionally important species and biophysical structures	Low abundance of wolverines and wolves in Low Arctic tundra [LP23]	Large predators	High	High		The wolf is extirpated in accordance with governmental policy, while a very limited number of reproducing wolverines is allowed for the same reason.

Table 7.2a. Continued

Ecosystem characteristic	Phenomenon	Indicator	Validity of phenomenon (VP)	Evidence for phenomenon (EP)		Comments EP
Landscape-ecological patterns	Increasing presence or cover of woody plants in snowbeds [LP24]	Snowbed encroachment	Intermediate	Intermediate	–	Proportion of monitoring plots in snowbeds that have occurrence of dwarf shrubs is increasing. In the eastern monitoring area (Komagdalen) this corresponds with an increase of about 20 % of the plots in 2009 to approx. 40 % of plots in 2020.
Landscape-ecological patterns	Decreasing total area that meets climate criteria for Low Arctic tundra zones D and E [LP25]	Bioclimatic subzones	Intermediate	High	–	Area that climatically is in the Low Arctic subzones D and E is strongly decreasing. Subzone D has nearly disappeared from the Low Arctic part of Finnmark.
Landscape-ecological patterns	Decreasing total area of wilderness areas [LP26]	Wilderness areas	Intermediate	Intermediate	–	Wilderness areas are much reduced relative to an intact reference condition without major technical infrastructure and EP is evaluated as intermediate. The percent area > 5 km from major infrastructure developments is today 38 % for tundra, and 24 % for the ecotone. Recent changes are minimal though, shown by the fact that the indicator is nearly unchanged over the monitoring period (1988–2018).
Biological diversity	Increased proportion of boreal and woody species at the expense of Arctic and herbaceous species [LP27]	Plant communities	Intermediate	Intermediate	–	Proportion of the species pool of strict Arctic-alpine distribution is decreasing relative to species with boreal and nemoral distribution, both in terms of species richness and species abundance.
Biological diversity	Absence of sustained increase in Arctic fox population despite conservation efforts [LP28]	Arctic fox abundance	High	Intermediate	–	The indicator is in a poor condition. Arctic fox population is historically low. Recent intensive conservation actions may have a positive effect, but it is too early to assess whether it will be sustained.
Biological diversity	Small or decreasing litter size of Arctic fox [LP29]	Arctic fox litter size	High	Intermediate	–	The indicator is in a poor condition with a low number of cubs per litter in the whole monitoring period in contrast to other populations where litter size strongly reacts to lemming abundance.

Table 7.2a. Continued

Ecosystem characteristic	Phenomenon	Indicator	Validity of phenomenon (VP)	Evidence for phenomenon (EP)		Comments EP
Biological diversity	Absence of sustained increase in the proportion of days with Arctic fox captures by camera traps despite conservation efforts [LP30]	Arctic fox camera index	High	High	–	The indicator is in a poor condition with very low occurrence of Arctic fox. Recent intensive conservation actions may have a positive effect, but it is too early to assess whether it will be sustained.
Biological diversity	Absence of breeding snowy owls during the majority of peak rodent years linked to low lemming abundance [LP31]	Snowy owl abundance	High	Intermediate	–	The indicator is in a poor condition because the species is on the National Red list as critically endangered. The lack of breeding snowy owls in 1/4 of the small rodent peaks in the time series coincide with this, but time series still too short to support "High" for EP.
Biological diversity	Low and/or decreasing snowy owl clutch size during peak rodent years [LP32]	Snowy owl fecundity	High	None	–	Since breeding snowy owls are lacking in 1/4 of the small rodent peaks, data do not support evaluation of change in size of clutch size.
Biological diversity	Decreasing abundance and species diversity among open tundra species [LP33]	Bird communities	Intermediate	High	–	High degree of evidence for decreasing species richness and smaller proportion of tundra species relative to thicket-associated species, due to a decrease in species associated with the open tundra habitats. The decrease in abundance and species richness of tundra species during the last 10 years is approximately 30–40 %.
Abiotic factors	Decreasing frequency of days with extreme cold [LP34]	Days with extreme cold	High	Intermediate	–	Days with extreme cold occurred in average every year under the climatic reference period in large parts of the ecotone. After 2000, extreme cold days have been nearly absent in the modelled climate data.
Abiotic factors	Increasing frequency of winter melt days [LP35]	Winter melt days	High	High	–	The number of winter melt days is increasing in tundra and ecotone, approximately 1.5 %/year since 1991. This corresponds to approx. 7 more winter melt days per year relative to the climatic reference period.

Table 7.2a. Continued

Ecosystem characteristic	Phenomenon	Indicator	Validity of phenomenon (VP)	Evidence for phenomenon (EP)		Comments EP
Abiotic factors	Increasing number of degree days [LP36]	Degree days	High	High	–	The number of degree days is strongly increasing in tundra and ecotone, approximately 0.7 days/year. This corresponds to approx. 20 more degree days per year relative to the climatic reference period.
Abiotic factors	Increasing growing degree day sum during the growing season [LP37]	Growing degree days	High	High	–	Growing degree days are strongly increasing in tundra and ecotone, approximately 4–5 degrees/year after 1991.
Abiotic factors	Increasing annual temperature [LP38]	Annual mean temperature	High	Intermediate	–	There is strong evidence that annual mean temperatures are increasing (approx. 0.6°C/decade for tundra and ecotone areas).
Abiotic factors	Increasing January temperature [LP39]	January mean temperature	High	Intermediate	–	There is strong evidence that January mean temperatures are increasing (approx. 0.8 degrees/decade for tundra and ecotone areas).
Abiotic factors	Increasing July temperature [LP40]	July mean temperature	High	High		There is strong evidence that July mean temperatures are increasing (approx. 0.3 degrees/decade for tundra and ecotone areas).
Abiotic factors	Changes in annual precipitation [LP41]	Annual precipitation	Intermediate	Low	–	Annual precipitation is increasing in tundra, to a lesser degree in the forest-ecotone. After 1991 it corresponds to approximately 3.5 mm/year for the whole tundra region in average.
Abiotic factors	Changes in precipitation during the growing season [LP42]	Precipitation during growing season	Intermediate	None	–	–
Abiotic factors	Shorter season with snow cover [LP43]	Snow cover duration	High	High	–	Snow cover duration has decreased with approximately 0.3 %/year after 1991, corresponding to approximately 20 days shorter snow season relative to the climatic reference period.
Abiotic factors	Increasing presence of basal ice/hard snow in the bottom layer [LP44]	Basal ice	High	None	–	Occurrence of basal ice is highly variable between years and between the two timeseries (high geographic variation), and there is no evidence for increasing occurrence of basal ice.

Table 7.2b. Assessment of the phenomena in High Arctic tundra. For definitions of categories and criteria, see Fig. 7.2. The assessment of the phenomenon, EP, can vary in different areas of the ecosystem being assessed and therefore two columns are presented. Details on VP is found under the phenomenon description for each indicator in section 5.1.2.

Ecosystem characteristic	Phenomenon	Indicator	Validity of phenomenon (VP)	Evidence for phenomenon (EP)		Comments to EP
Primary productivity	Changes in maximum productivity — greening and browning [HP01]	Maximum vegetation productivity	High	Low	—	Maximum vegetation productivity is increasing (greening), e.g. in the large valleys on Nordenskiöld Land. Very few areas show the opposite tendency.
Primary productivity	Earlier start of growing season [HP02]	Start of growing season	High	Low	—	Significant earlier growth season occurs at various places in all bioclimatic zones, but mainly on Nordenskiöld Land.
Biomass distribution among trophic levels	Changes in the ratio of maximum vegetation productivity to Svalbard reindeer abundance [HP03]	Maximum vegetation productivity versus Svalbard reindeer	Intermediate	None	—	—
Biomass distribution among trophic levels	Increased geese biomass in relation to plants in the food web [HP04]	Maximum vegetation productivity versus geese	Intermediate	Intermediate	—	Large degree of evidence for increasing goose biomass relative to plant productivity, but both plant productivity and goose abundance show increasing trends. There is no evidence that the change is of ecosystem significance at present.
Biomass distribution among trophic levels	Changes in the biomass relationship between herbivorous vertebrates and Arctic fox [HP05]	Herbivorous vertebrates versus Arctic fox	Low	Intermediate	—	Large degree of evidence for changes due to increasing populations of herbivores. At present there is no evidence that the change is of ecosystem significance.
Functional groups within trophic levels	Changes in the composition of that functional group of herbivorous vertebrates [HP06]	Herbivorous vertebrates	Intermediate	None	—	—
Functionally important species and biophysical structures	Changes in the abundance of pink-footed goose [HP07]	Pink-footed goose abundance	High	Intermediate	—	Large degree of evidence for increased pink-footed goose abundance. At present there is no evidence that the change is of ecosystem significance.

Table 7.2b. Continued

Ecosystem characteristic	Phenomenon	Indicator	Validity of phenomenon (VP)	Evidence for phenomenon (EP)		Comments to EP
Functionally important species and biophysical structures	Changes in the abundance of barnacle goose [HP08]	Barnacle goose abundance	High	Intermediate	–	Large degree of evidence for increasing barnacle goose abundance. At present there is no evidence that the change is of ecosystem significance.
Functionally important species and biophysical structures	Decrease in the abundance of Svalbard reindeer [HP09]	Svalbard reindeer abundance	High	Low	Intermediate	EP is divided between two categories because the degree of evidence varies between study areas. The population is strongly increasing in Adventdalen/Reindalen, but weak to decreasing on Brøggerhalvøya.
Functionally important species and biophysical structures	High or increasing mortality rate in Svalbard reindeer [HP10]	Svalbard reindeer mortality rate	High	None	–	–
Functionally important species and biophysical structures	Low or decreasing calf rate of Svalbard reindeer [HP11]	Svalbard reindeer calf rate	High	None	–	–
Functionally important species and biophysical structures	Decreasing abundance of Arctic fox [HP12]	Arctic fox abundance	Intermediate	None	–	New modelling results (Nater et al. 2021) show the Arctic fox population is presently subjected to multiple drivers in such a manner that the total driver load stabilises the population.
Landscape-ecological patterns	Decreasing total area that meets climate criteria for the High Arctic tundra zones A, B, and C [HP13]	Bioclimatic subzones	Intermediate	High	–	The area, climatically located in the High Arctic zone A, is strongly decreasing. Note that based on biases in the dataset related to cold temperatures (Appendix 8.2), it is likely that the size of the area of the coldest zone is overestimated.

Table 7.2b. Continued

Ecosystem characteristic	Phenomenon	Indicator	Validity of phenomenon (VP)	Evidence for phenomenon (EP)		Comments to EP
Landscape-ecological patterns	Decreasing total area of wilderness areas [HP14]	Wilderness areas	Intermediate	Low	–	INON area is slightly reduced relative to an intact condition without major technical infrastructure and EP is subsequently evaluated as low. INON is, however, virtually unchanged over the monitoring period (1990–2015). Areas > 1 km from infrastructure in zone C 1990–2015: 95.1–95.0%.
Biological diversity	Decreasing abundance of breeding Svalbard rock ptarmigan [HP15]	Svalbard rock ptarmigan breeding abundance	Intermediate	None	–	There has been an increase in rock ptarmigan breeding abundance during the last decade, hence a trend that runs counter to the current phenomenon for this indicator. The phenomenon should be revised based on new research before the next assessment (Marolla et al. 2021).
Abiotic factors	Decreasing frequency of days with extreme cold [HP16]	Days with extreme cold	Intermediate	Intermediate	–	The number of days with extreme cold is strongly decreasing in the order of magnitude 16%/year. The ecological significance of these changes has been evaluated as low, but recent studies have indicated increasing winter temperatures as an important predictor for increased Svalbard rock ptarmigan breeding abundance. However, the understanding of the role of the indicator in the ecosystem is still limited.
Abiotic factors	Increasing frequency of winter melt days [HP17]	Winter melt days	High	High	–	The number of winter melt days are increasing in the order of magnitude 3–4%/year since 1991. This corresponds for Longyearbyen to approx. 7 days more winter melt days per year relative to the climatic reference period.
Abiotic factors	Increasing number of degree days [HP18]	Degree days	High	Intermediate	–	Number of degree days increased around 6 days per year in the period 1991–2019 for subzone C.

Table 7.2b. Continued

Ecosystem characteristic	Phenomenon	Indicator	Validity of phenomenon (VP)	Evidence for phenomenon (EP)		Comments to EP
Abiotic factors	Increasing growing degree day sum during the growing season [HP19]	Growing degree days	High	Intermediate	–	Increasing growing degree day sum of 8%/year in all three subzones.
Abiotic factors	Increasing annual mean temperature [HP20]	Annual mean temperature	High	High	–	Increasing temperatures of 0.12°C per year in all subzones, corresponding to a 3°C increase in temperature since 1991.
Abiotic factors	Increasing July temperature [HP21]	July mean temperature	High	High	–	The July temperature is increasing in the order of magnitude 0.06 degrees/year.
Abiotic factors	Changes in annual precipitation [HP22]	Annual precipitation	Intermediate	Low	–	Low degree of evidence for increasing annual precipitation, but the change is small and evaluated to have small ecological significance.
Abiotic factors	Increasing permafrost temperature in the upper 15 m [HP23]	Permafrost	High	Intermediate	–	High degree of evidence for increasing permafrost temperature. For the time being low expected biological importance of observed changes.
Abiotic factors	Increased thickness of the active layer [HP24]	Permafrost	High	Intermediate	–	High degree of evidence for increasing depth in the active layer. At present there is no evidence that the change is of ecosystem significance.
Abiotic factors	Shorter snow season [HP25]	Snow cover duration	High	High	–	The snow cover duration has decreased with ca. 0.2 %/year after 1991 corresponding to approx. three weeks shorter snow season today relative to the climatic reference period.

7.3 Assessment of ecosystem condition

Following the PAEC protocol (Jepsen et al. 2020), the assessment of the condition of the Arctic tundra ecosystem consists of the following sections: We first present the assessment of the condition of each ecosystem characteristics based on all phenomena (7.3.1), then the assessment of the condition of the ecosystem as a whole (7.3.2), followed by a discussion of likely future trajectories for ecosystem condition (7.3.3). Lastly, we present recommendations for further monitoring and research.

7.3.1 Assessment of the condition of individual ecosystem characteristics

In the following we present the assessment of the condition of each of the seven ecosystem characteristics (Box 2). The assessment is supported by 1) Appendix 8.1 and 8.2, which supply time series plots and trend analysis for each indicator, associated state variables and background data for Low and High Arctic indicators, respectively, and 2) the PAEC assessment diagrams (Fig. 7.3.1a for Low Arctic tundra and Fig. 7.3.1b for High Arctic tundra). The diagrams provide an overview of all phenomena across all ecosystem characteristics based on the *evidence for the phenomenon* (EP, x-axis) and the *validity of the* phenomenon (VP, y-axis). Note that phenomena which are scored as "insufficient" at the EP-axis should not be accounted for in the assessment, but are plotted to highlight phenomena for which data coverage and/or quality should be improved for future assessments. Depending on the distribution of all other phenomena in the diagram, the ecosystem characteristics is scored to one of three categories briefly defined below. The criteria for the three assessment categories are described in Box 3 (see Jepsen et al. 2020 for details).

In the following we describe the assessments of the ecological condition for the seven ecosystem characteristics for Low Arctic tundra (Fig. 7.3.1a) and High Arctic tundra (Fig. 7.3.1b) graphically in the form of assessment diagrams followed by a written description of the assessment of each ecosystem characteristic.

A typical landscape of Low Arctic tundra in Finnmark. The vegetation consists of herbaceous and woody plants, with woody plants being prostrate, dwarf or low-statured shrubs. High annual variation in temperature and precipitation causes variation in the onset of the growing season, as well as variation in the conditions for growth during the growing seasons. Photo: G. Vie/UiT

Box 3. Summary of the criteria for the three assessment categories and general considerations for this assessment. Details are described in Jepsen et al. (2020).

No deviation from the reference condition

An ecosystem characteristic assigned to this category shows no or very limited deviations from the reference condition. According to the definition of the reference condition, the ecosystem characteristic can be considered in good ecological condition based on the current set of indicators.

- Most or all of the phenomena should be in the green cells in the PAEC assessment diagram (Fig. 7.3.1a, b).
- Most or all phenomena should have either no evidence (EP=None), or low evidence (EP=Low) in combination with a low validity (VP=Low).
- This category can usually be assigned with high confidence, since there is no evidence that changes of ecosystem significance have occurred. In such cases uncertain links to drivers or a poor understanding of the implications of changes is less of a concern.
- If any phenomena are located in the orange or red cells, the choice of category *No deviations from the reference condition* should be justified in the textual assessment.

Limited deviation from the reference condition

An ecosystem characteristic assigned to this category shows limited deviations from the reference condition. According to the definition of the reference condition, the ecosystem characteristic can still be considered in good ecological condition based on the current set of indicators. However, individual indicators show changes in a direction of a worsened ecological condition, which requires attention.

- Most or all of the phenomena should be in the orange cells in the PAEC assessment diagram (Fig. 7.3.1a, b).
- Most or all phenomena should have either low evidence (EP=Low) or intermediate evidence (EP=Intermediate) in combination with a low-intermediate validity (VP=Low or Intermediate).
- This category is often assigned with lower confidence than the other two categories, since it can include phenomena which both have low to intermediate validity and a high level of evidence for change. These are the most uncertain phenomena to assess.
- If any phenomena are located in the green or red cells, the choice of category *Limited deviation from the reference condition* should be justified in the textual assessment.

Substantial deviation from the reference condition

Ecosystem characteristics assigned to this category show substantial deviations from the reference condition. According to the definition of the reference condition, they can NOT be considered in good ecological condition based on the current set of indicators.

- Most or all of the phenomena should be in the red cells in PAEC assessment diagram (Fig. 7.3.1a, b).
- Most or all phenomena should have intermediate to high evidence (EP=Intermediate or High) in combination with intermediate to high validity (VP=Intermediate or High).
- This category can usually be assigned with high confidence, since most phenomena have high validity, and a high level of evidence.
- If any phenomena are located in the green or orange cells, the choice of category *Substantial deviation from the reference condition* should be justified in the textual assessment.

General considerations for this assessment:

The choice of assessment category for an ecosystem characteristic is hence guided by the centre of gravity of the set of phenomena representing the characteristic, as outlined in the definition of the categories above. This can be challenging when the characteristic is represented by a set of indicators that is assessed as “inadequate”, or when phenomena are spread across several or all categories. In such cases, the choice of assessment category is supported by a justification that highlights why more emphasis has been placed on certain phenomena. This can be justified by better data coverage, higher validity or an understanding that certain phenomena are of higher relevance (e.g. terms of ecological significance) than others for the condition of the ecosystem characteristic as a whole. Similarly, the assessment of the ecosystem as a whole has been guided by an understanding of the relative importance of the different characteristics for the condition and/or integrity of the ecosystem as a whole.

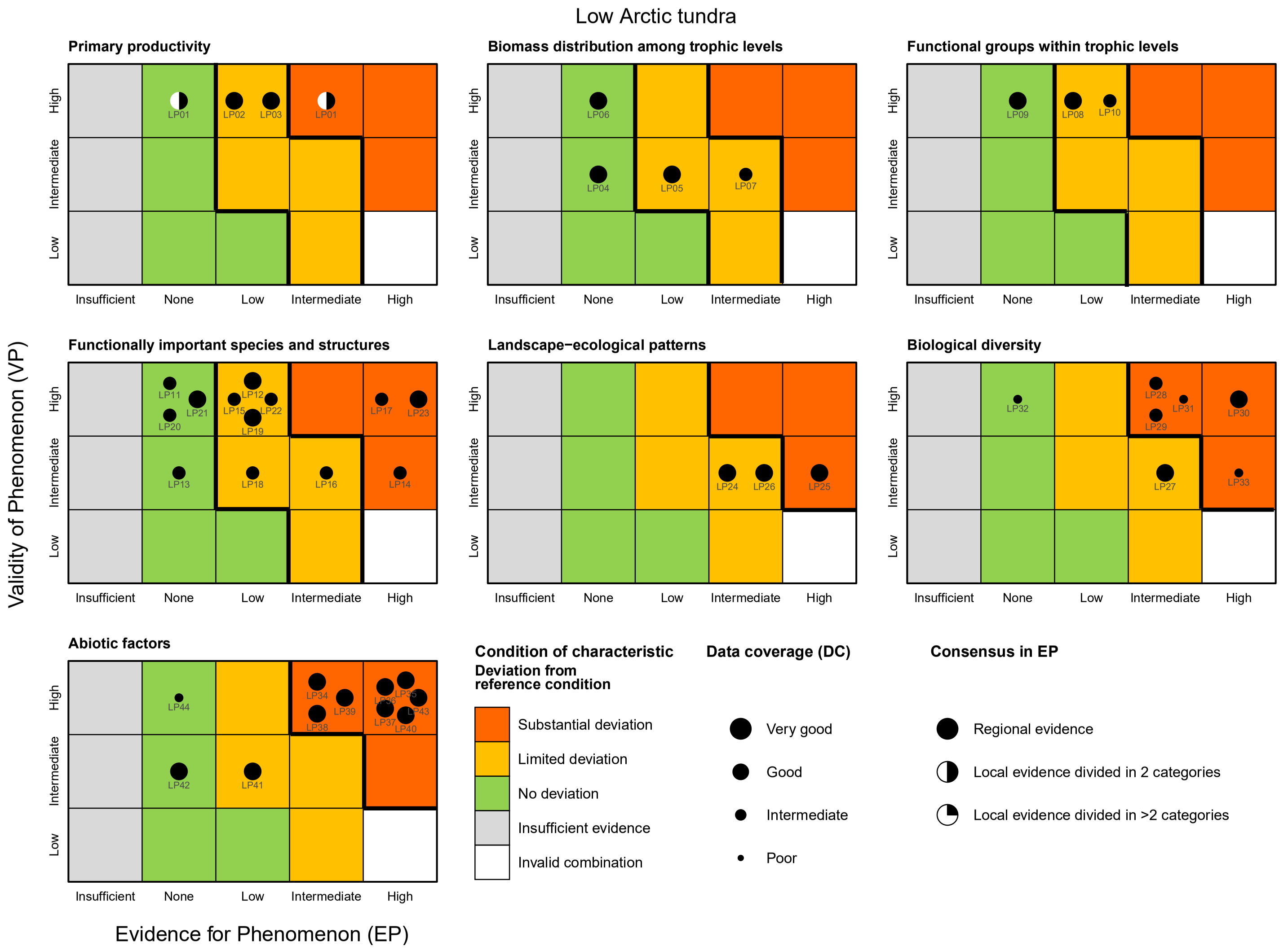


Figure 7.3.1a. The PAEC assessment diagram provides an overview of all phenomena for all ecosystem characteristics. Each dot represents the assessment of a phenomenon with ID (from Table 5.1a). The size of the dot indicates the data coverage (DC; larger symbols = better coverage, from Table 7.1a). The placement of the dot shows the value for the validity (VP) of the phenomenon and the levels of evidence (EP) for the phenomenon (from Table 7.2a). Note that phenomena which are scored as EP=Insufficient, should not be accounted for in the assessment, but are plotted to highlight phenomena for which data coverage and/or quality should be improved for future assessments. Bold lines around the coloured boxes, within the diagrams for each of the ecosystem characteristics, indicate the condition of the respective characteristic.

Low Arctic tundra — Primary productivity

Assessment category: Based on the set of indicators this ecosystem characteristic is assessed as having **limited deviation from the reference condition**. This means that the ecosystem characteristic can be considered in good ecological condition. There is evidence of changes towards a worsened condition consistent with phenomena attributed to climate change, but the magnitudes of these changes are so small and/or heterogeneous that they are assessed to have overall limited impact on the ecological condition.

Justification for choice of assessment category: This assessment is based on three indicators with associated phenomena (LP01, LP02 and LP03) that are of high validity (VP) with respect to their climatic drivers and their potentially pervasive impacts on the other ecosystem characteristics. However, these indicators/phenomena score mostly low on the EP axis based on the estimated changes based on time series analyses. Consequently, two of the phenomena (LP02 indicator *Start of Growing season* and LP03 indicator *Plant biomass*) become located in the "limited deviation" section of the assessment diagram (Fig. 7.3.1a). The third phenomenon (LP01 indicator *Maximum vegetation productivity*) is split between the "no deviation" and "substantial deviation" sections. This is because there is spatially contrasting evidence for changes in vegetation productivity that can be attributed to different climate change related phenomena in the tundra (greening) and the forest-tundra ecotone (browning) as well as regions which show no trend in vegetation productivity. The primary mechanism behind observed browning trends in the ecotone is defoliation of shrubs and trees due outbreaks by geometrid moth. The ecological significance of this phenomenon, which is known to be regionally substantial, is emphasised under the ecosystem characteristics *Functionally important species and biophysical structures*.

Uncertainties related to the choice of assessment category: There are no major uncertainties related to the choice of category. The three indicators all have very good data coverage. The observed changes are in line with expectations based on observed trends in other parts of the Arctic. The indicator coverage of the ecosystem characteristic as a whole is assessed as partially adequate, mainly due to absence of plant phenology field data.

Low Arctic tundra — Biomass distribution among trophic levels

Assessment category: Based on the set of indicators this ecosystem characteristic is assessed as having **limited deviation from the reference condition**. This means that the ecosystem characteristic can be considered in good ecological condition. There is evidence of changes towards a worsened condition with stronger boreal influence, but the magnitudes of these changes are such that they are assessed to have overall limited impact on ecological condition. There are uncertainties related to the choice of category.

Justification for choice of assessment category: This assessment is based on four indicators with four associated phenomena (LP04, LP05, LP06, and LP07) that are of intermediate to high validity (VP) with mostly certain links to relevant anthropogenic drivers, but a less good understanding of the significance of changes in biomass ratios across trophic levels related to ecosystem condition. The two phenomena belonging to the food chain plants—ungulates—carnivores [LP05, LP07] show some evidence of change and are located in the "limited deviation" section of the diagram. This is due to increasing plant biomass (LP05 indicator *Plant growth forms versus ungulates*), and an increasing presence of red fox (LP07 indicator *Ungulates versus carnivorous vertebrates*). The latter phenomenon is the one most clearly linked to an increasing boreal influence on the ecosystem, but also to the long-term policy of eliminating large carnivores from the ecosystem ("mesopredator release"). The two phenomena belonging to the food chain plants—rodents—carnivores (LP04 indicator *Plant growth forms versus rodents*, LP06 indicator *Rodents versus carnivorous vertebrates*) show no evidence that the expected changes in ratios across trophic levels have occurred (EP = None) and hence end up in the "no deviation" section of the diagram. With two phenomena placed in each of two categories there are uncertainties related to the choice of assessment category (see below). However, due to policy-driven elimination of top predators that naturally belong to the ungulate-based predator—prey link in the food web, the positioning of LP7 is emphasised for the overall categorisation of the ecosystem characteristic.

Uncertainties related to the choice of assessment category: There are uncertainties related to the choice of category, due to the equal distribution of phenomena across two categories. All four indicators have good to very good data coverage. The indicator coverage of the ecosystem characteristic is assessed as partially adequate because the indicators include the trophic levels in the two dominant food chains: 1) plants—rodents—carnivores and 2) plants—ungulates—carnivores, though with a less good representation of carnivores, notably a lack of large predators, in the latter.

Low Arctic tundra — Functional groups within trophic levels

Assessment category: Based on the set of indicators the ecosystem characteristic is assessed as having **limited deviation from the reference condition**. This means that the ecosystem characteristic can be considered in good ecological condition. There is evidence of changes towards a worsened condition with stronger boreal influence, but the magnitudes of these changes are such that they are assessed to have overall limited impact on ecological condition.

Justification for choice of assessment category: This assessment is based on three indicators with three associated phenomena (LP08, LP09, LP10) that are of high validity (VP) with certain links to relevant anthropogenic drivers and a good understanding of their potentially pervasive impacts on the other ecosystem characteristics. Two phenomena related to plant and carnivore functional groups (LP08 indicator *Plant growth forms* and LP10 indicator *Carnivorous vertebrates*) are located in the "limited deviation" section of the diagram. LP08 focuses on the ratio between palatable and unpalatable plants. There is some evidence of a development towards a less good condition of the ecosystem (i.e. increasing dominance of unpalatable plants), but the changes are small and yet of relatively unclear ecological significance. LP10 focuses on borealisation, and the ratio between Arctic and boreal carnivores. It shows some evidence of increasing borealisation because the red fox populations are increasing relative to the Arctic fox populations in the control areas where red foxes are not actively culled. This is a development towards a worsened condition with increasing pressure on the native Arctic fox through competition. The third phenomenon related to herbivore functional groups (LP09 indicator *Herbivorous vertebrates*), shows regional evidence for increasing borealisation in the rodent functional group (lemming:voles), but not for large herbivores. For this reason, the phenomena as a whole are located in the "no deviance" section of the diagram.

Uncertainties related to the choice of assessment category: There are no major uncertainties related to the choice of category. All three indicators have good to very good data coverage but lack boreal raptors/scavengers like crows and ravens. The indicator coverage of the ecosystem characteristic is nevertheless assessed as adequate because these indicators cover the three most important functional groups plants, herbivores and carnivores.

Low Arctic tundra — Functionally important species and biophysical structures

Assessment category: Based on the set of indicators the ecosystem characteristic is assessed as having **limited deviation from the reference condition**. This means that the ecosystem characteristic can be considered in good ecological condition. There is evidence of changes towards a worsened condition with stronger boreal influence attributed to climate change, but the magnitudes of these changes are such that they are assessed to have overall limited impact on ecological condition. However, the ecotone portion of the ecosystem characteristic is assessed as having substantial deviations from the reference condition, primarily due to climate change intensified outbreaks by geometrid moth causing high forest and shrub mortality. There are uncertainties related to the choice of category.

Justification for choice of assessment category: This ecosystem characteristic is the most challenging to assess for two reasons. Firstly, the set of 10 indicators and 13 associated phenomena (LP11-LP23) represents a diversity of ecological functions and structures of mostly high validity (VP), which are split between two parts the ecosystem; namely tundra and the forest-tundra ecotone. Secondly, the phenomena linked to the indicators exhibit a wide spread on the EP axis ranging from no to high evidence, consequently, yielding assessments of the phenomena in the range of no to substantial deviation from the reference condition. Hence, the overall assessment must consider the relative importance of the deviations in the two parts of the ecosystem system (tundra versus the ecotone) and the relative significance of the phenomena for the overall condition of the ecosystem. For the present ecosystem characteristic to be overall placed in the category "substantial deviation", several phenomena of fundamental implications for the condition of the whole ecosystem must be assessed to be in this category. In the present assessment, only three of the phenomena are located in the "substantial deviation" of the diagram. Two of these, which are located in the ecotone, are due to the climatically intensified geometrid moth outbreak; LP17 (indicator *Geometrid moth outbreaks)* and LP14 (indicator *Mountain birch in forest-tundra)*. They have high ecological significance in terms of substantial forest and shrub mortality in the ecotone and, moreover, spill-over effects to the tundra in terms of reduced *Ptarmigan density* (LP16; "limited deviation") and spread of new moth species into tundra with implications in terms of mortality of willow shrubs (LP18; "limited deviation"). These effects raise concern regarding a potential continued spread into shrub tundra further from the coast and the ecotone. However, since the implications of moth outbreaks are still predominantly restricted to the ecotone part of the ecosystem, and their spill-over effects still cause only limited deviations in a minority of the tundra functions, they are not assessed to be decisive for the overall assessment of the ecosystem characteristic. The third indicator having substantial deviation from the reference condition is *Large predators* (LP23), which due to political management decisions is much reduced (wolverine) or eliminated (wolf). Although the function large carnivores in the Low Arctic food web has been lost, the implication is assessed to be not decisive for the overall assessment of the ecosystem characteristic. The bulk of the phenomena (N = 6) is located in the "limited deviation" section of the diagram. These include fundamentally important plants (LP12), key herbivores (LP15, LP16, LP19) and predators (LP22) in Low Arctic tundra. Hence, the assessment of these phenomena is consistent with, and decisive for, the overall assessment of this ecosystem characteristic.

Uncertainties related to the choice of assessment category: There are uncertainties related to the choice of category, despite an extensive set of indicators with good to very good data coverage. This is due to the phenomena being spread over all three categories, and the before mentioned dichotomy between tundra and ecotone processes. Some uncertainty should also be attributed to the indicator coverage which is assessed as "partially adequate". The assessment could be strengthened by including functionally important species such as mountain birch in tundra, as well as detritivores and pollinating insects.

Low Arctic tundra — Landscape-ecological patterns

Assessment category: Based on the set of indicators the ecosystem characteristic is assessed as having **substantial deviation from the reference condition**. This means that the ecosystem characteristic cannot be considered in good ecological condition. This is primarily due to a complete loss of areas which climatically belong to the Arctic bioclimatic subzone D (Southern Arctic tundra). Over time this transition towards a climate more indicative of shrub tundra or boreal forest will not permit the maintenance of structurally and functionally intact Low Arctic ecosystems. There are uncertainties related to the choice of category.

Justification for choice of assessment category: The assessment is based on three indicators, with three associated phenomena (LP24, LP25, LP26) that are of intermediate validity (VP), due to certain links to anthropogenic drivers, but a less good understanding of their potential pervasive effects on ecosystem condition. All three phenomena (LP24 indicator *Snow bed encroachment*, LP25 indicator *Bioclimatic subzones,* and LP26 indicator *Wilderness areas*), show high evidence for change, but the phenomena *Wilderness areas* (*LP26*) and *Snowbed encroachment* (*LP24*) have intermediate EP, and are hence located in the "limited deviation" section of the diagram, because the changes are expected to be of less ecosystem significance. The third phenomenon (LP25 Bioclimatic subzones) is located in the "substantial deviation" section of the diagram. This indicator tracks the distribution of the three Low Arctic Bioclimatic subzones according to their climatic definition (based on Mean July temperature). The observed changes in this indicator are dramatic and are considered of higher relevance for the condition of this ecosystem characteristic than the remaining two phenomena. During the climatic reference period 1961–1990 the area of subzone D (Southern Arctic tundra) had similar extent as subzone E (Arctic shrub-tundra) in Low Arctic tundra and covered most of the area in eastern regions (Varanger Peninsula). Currently (after 2010) all regions in the Low Arctic tundra are climatically in subzone E, Arctic shrub-tundra. In a climatic sense, the coldest bioclimatic subzone has hence vanished relative to the climatic reference period. This transition towards a more boreal climate suggests that also biotic transition towards shrub tundra can be expected to happen over time. Increasing occurrence of woody plants in snow beds (LP24) is already observed. Contrary to LP24 and LP25 for which changes are driven mainly by climate change, the indicator *Wilderness areas* (LP26) is controlled by infrastructure development. Although wilderness areas are almost unchanged since the beginning of the monitoring period (~2% reduction in tundra area from 1988–2018), the area before 1988 was already reduced to an extent which constitutes a deviation from an intact reference condition (approximate 40% (70%) of tundra areas was located > 5 km (> 1 km) from major technical installations in 1988).

Uncertainties related to the choice of assessment category: There are uncertainties related to the choice of category. The assessment is based on just three indicators, with very good data coverage, but important landscape-ecological patterns related to vegetation zonation (regional thicket prevalence in tundra and climatic/empirical forest limit and tree line) are missing (indicator coverage is partially adequate). The three phenomena are located in two categories. The choice of category reflects that one of these phenomena is considered of higher relevance for the overall condition of the ecosystem characteristics than the remaining two.

Low Arctic tundra — Biological diversity

Assessment category: Based on the set of indicators the ecosystem characteristic is assessed as having **substantial deviation from the reference condition**. This means that the ecosystem characteristic cannot be considered in good ecological condition. Several characteristic Arctic species are critically endangered (Arctic fox) or absent in expected breeding years (Snowy owl). Low Arctic bird and plant communities show an increasing degree of climate change related borealisation, especially for the bird community the rate of change is fast. The observed changes point to a loss of integrity of the Low Arctic ecosystem.

Justification for choice of assessment category: This assessment is based on seven indicators, with seven associated phenomena (LP27-LP33) that focus on typical Arctic species that are of importance to the integrity of the target ecosystem. Five of them represent two iconic Arctic species (Arctic fox and snowy owl), and two of them biodiversity of important communities (vascular plants and birds). All phenomena have intermediate to high validity (VP) with relatively certain links to anthropogenic drivers and good understanding of the indicator's role in the Low Arctic ecosystem (Fig. 7.3.1a). Five phenomena are located in the "substantial deviation" section of the diagram, one in the "limited deviation" and one in the "no deviation" section. Phenomena related to the Arctic fox (LP28 indicator *Arctic fox abundance*, LP29 indicator *Arctic fox litter size*, LP30 indicator *Arctic fox camera index*), are all located in the "substantial deviation" section of the diagram. This is due to the fact that the species is critically endangered with populations much below what would be expected for the reference condition (an "intact" Low Arctic ecosystem). The Arctic fox has experienced low population densities and litter sizes during the monitoring period compared to lemming-controlled populations elsewhere in the Low Arctic. However, current management actions to increase Arctic fox populations already show a slight positive effect on the population size and it is expected that this population increase will continue. "Substantial deviation" is also the category for LP33 (indicator *Bird communities*) which experiences fast decreasing species richness and increased dominance of bird species linked to thicket habitats (i.e. more boreal species). An increasing borealisation is also indicated in *Plant communities* (LP27), where the proportion of species with a strict Arctic-alpine distribution is decreasing relative to species with a boreal-nemoral distribution. Snowy owl (LP31 indicator *Snowy owl abundance*), which is a species expected to breed regularly in the Low Arctic tundra during rodent peak years, has only been observed breeding in one-fourth of the cyclic rodent peak years in the 16-year long time series, most likely due to the low abundance of lemmings in those peak years. This must be considered a substantial deviation from the reference condition. To the extent to which the species breed however, there is no evidence of low clutch size (LP32 indicator *Snowy owl fecundity*) relative to other Arctic populations, and LP32 is hence in the "no deviation" section of the diagram. However, the phenomena linked to snowy owls (LP31–LP32) have limited data coverage and are therefore less emphasised in this assessment compared to the other phenomena.

Uncertainties related to the choice of assessment category: There are no major uncertainties related to the choice of category. The data coverage of three of the indicators, *Snowy owl abundance* (LP31), *Snowy owl fecundity* (LP32) and *Bird communities* (LP33), is poor, while the other indicators have good to very good data coverage. The indicator coverage of the ecosystem characteristic is assessed as partially adequate, mainly due to absence of indicators on several important groups, for instance arthropod diversity. It should also be noted that five of the phenomena are associated with different aspects related to the same two Arctic species, Arctic fox and Snowy owl, meaning that the assessment of this ecosystem characteristic is highly influenced by the condition of these species.

Low Arctic tundra — Abiotic factors

Assessment category: Based on the set of climate related indicators the ecosystem characteristic is assessed as having **substantial deviation from the reference condition**. This means that the ecosystem characteristic cannot be considered in good ecological condition. The observed changes are dramatic and have occurred over the entire Low Arctic tundra and the ecotone. Several indicators are close to or exceed the historical observed variation during the reference period, in other words, values which during the 1961–1990 period were considered extreme are now within the expected norm.

Justification for choice of assessment category: This assessment is based on eleven indicators with eleven associated phenomena (LP34-LP44) with intermediate to high validity meaning certain links to anthropogenic drivers (climate change) and relatively good understanding of their role in the Low Arctic ecosystem. Lowest validity is attached to the phenomena related to precipitation (LP41 indicator *Annual precipitation* and LP42 indicator *Precipitation during the growing season*) for which we have a less good understanding of the importance of changes. Of the 11 phenomena, eight show high evidence for changes of ecosystem significance and hence are located in the "substantial deviation" section of the diagram. The exceptions are LP42 (indicator *Precipitation during the growing season*), and LP44 (indicator *Basal ice*) which show no evidence for change and hence are located in the "no deviation" section, and LP41 (indicator *Annual precipitation*) which shows some evidence of change, but of low expected ecosystem significance, and hence is located in the "limited deviation" section. However, for Low Arctic tundra, the two phenomena related to precipitation are considered of less relevance for the ecosystems ecological condition than indicators related to temperature and snow/ice, and more emphasis is hence placed on the latter in the assessment. The observed changes are substantial. For instance, LP38 (indicator *Annual mean temperature*) has increased from a historical range expected to permit discontinuous permafrost, to an above-zero range where discontinued permafrost cannot be expected to be sustained over time. The Low Arctic tundra today has almost three weeks shorter snow season (LP43 indicator *Snow cover duration*) and about 20 more degree days each year (LP36 indicator *Degree days*) compared to the climatic reference period (1961–1990). The indicators, *Degree days* (LP36) and *Growing degree days* (LP37), in Low Arctic tundra are similar or higher than the degree days observed in the forest-tundra ecotone under the climatic reference period (Appendix 8.1). The Low Arctic tundra is currently on an abiotic change trajectory which over time will not permit the maintenance of structurally and functionally intact Low Arctic ecosystems.

Uncertainties related to the choice of assessment category: There are no major uncertainties related to the choice of category. The data coverage of the indicators is very good, except for the indicator *Basal ice* that has intermediate data coverage. The indicator coverage of the ecosystem characteristic is assessed as partially adequate despite an extensive set of indicators. This is due to the absence of indicators that characterises regional snow quality, including snow structure, regional extent of basal ice and "rain-on-snow" events, which would allow more direct causal links to be established between abiotic conditions and biotic ecosystem characteristics. Further, albedo, which represents the reflective qualities of the surface in late winter/spring, is another important indicator not included in this assessment, which would allow closer causal links between biotic land surface changes (shrub encroachment), abiotic conditions (snow cover, snow melt) and regional climate feedbacks (through changes in the reflective properties of the land surface) to be established.

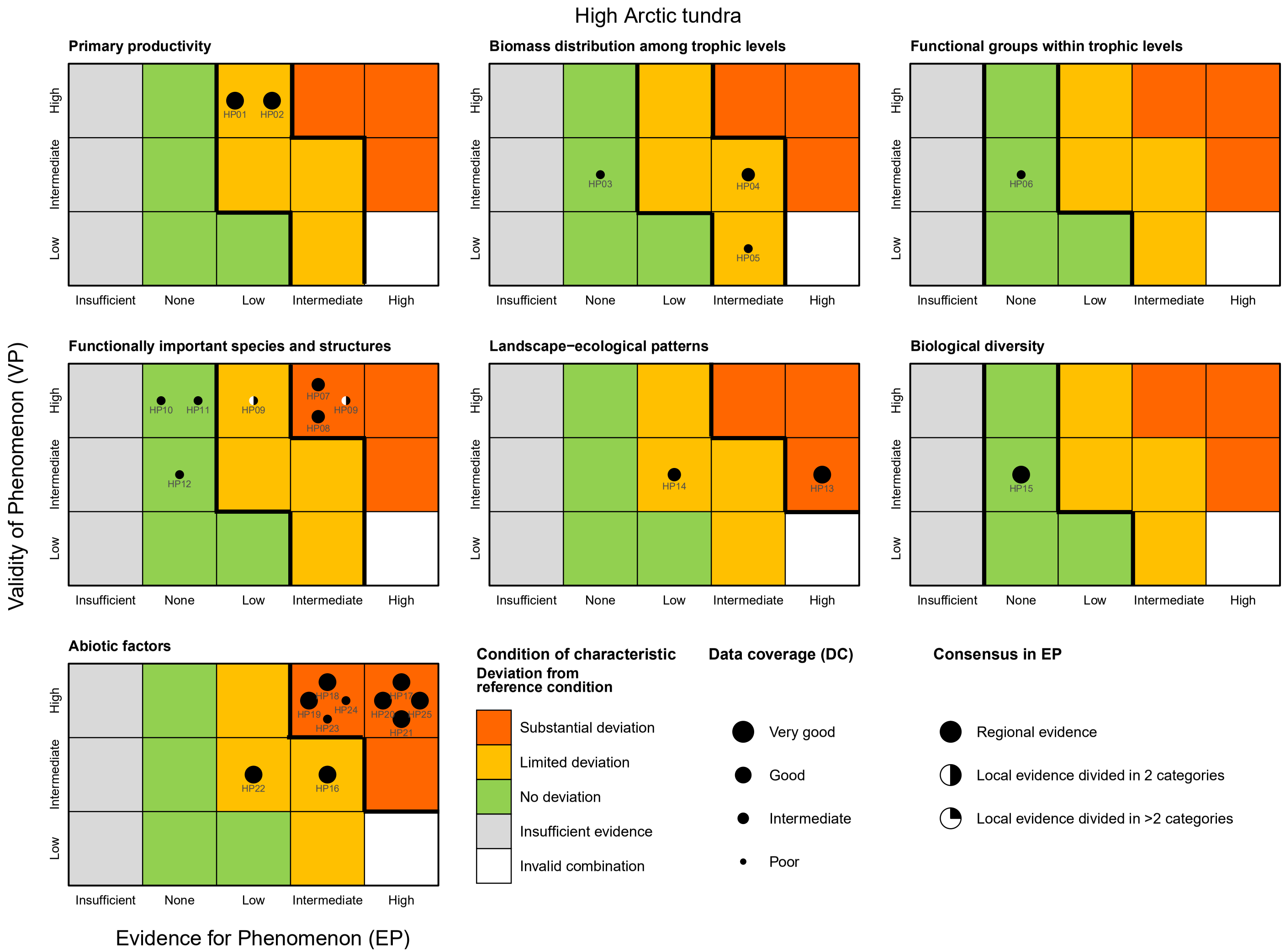


Figure 7.3.1b The PAEC assessment diagram provides an overview of all phenomena for all ecosystem characteristics. Each dot represents the assessment of a phenomenon with ID (from Table 5.1b). The size of the dot indicates the data coverage (DC; larger symbols = better coverage, from Table 7.1b). The placement of the dot shows the value for the validity (VP) of the phenomenon and the levels of evidence (EP) for the phenomenon (from Table 7.2b). Note that phenomena which are scored as EP=Insufficient, should not be accounted for in the assessment, but are plotted to highlight phenomena for which data coverage and/or quality should be improved for future assessments. Bold lines around the coloured boxes, within the diagrams for each of the ecosystem characteristics, indicate the condition of the respective characteristic.

High Arctic tundra — Primary productivity

Assessment category: Based on the set of indicators the ecosystem characteristic is assessed as having **limited deviation from the reference condition**. This means that the ecosystem characteristic can be considered in good ecological condition. There is evidence of changes towards a worsened condition consistent with phenomena attributed to climate change, but the magnitudes of these changes are so small and/or heterogeneous that they are assessed to have overall limited impact on ecological condition.

Justification for choice of assessment category: This assessment is based on two indicators, with two associated phenomena (HP01 indicator *Maximum vegetation productivity* and HP02 indicator *Start of growing season*). Both have high validity with certain links to anthropogenic drivers and good understanding of their role in the High Arctic ecosystem. Parts of the High Arctic tundra in Svalbard show significant greening trends and earlier onset of spring, but this is spatially highly variable. For this reason, the phenomena are considered to have a low level of evidence for the expected changes and the ecosystem significance of these changes are still considered limited (EP = Low). They are hence located in the "limited deviation" section of the diagram.

Uncertainties related to the choice of assessment category: There are no major uncertainties related to the choice of category. Both phenomena are based on remote sensing data sources and have very good data coverage. The indicator coverage, however, is assessed as inadequate due to the absence of field data on plant productivity or biomass.

High Arctic tundra — Biomass distribution among trophic levels

Assessment category: Based on the set of indicators this ecosystem characteristic is assessed as having **limited deviation from the reference condition**. This means that the ecosystem characteristic can be considered in good ecological condition. Increasing herbivore abundances, in particular populations of Arctic geese, cause shifts in biomass ratios. There are uncertainties regarding the choice of category.

Justification for choice of assessment category: This assessment is based on three indicators with three associated phenomena (HP03, HP04 and HP05) that are of low to intermediate validity (VP) with mostly certain links to relevant anthropogenic drivers, but a less good understanding of the significance of changes in biomass ratios across trophic levels related to ecosystem condition. The two phenomena associated with the indicators, *Herbivorous vertebrates versus Arctic fox* (HP05) and *Maximum vegetation productivity versus geese* (HP04), have intermediate level of evidence that the observed changes have occurred, mainly due to increased herbivore abundance, but currently limited ecosystem significance of observed changes. They are hence located in the "limited deviation" section of the diagram. Increasing abundance of Arctic geese, is associated with locally reduced plant biomass, and to some extent also soil erosion over broader areas. The phenomenon associated with the indicator *Maximum vegetation productivity versus Svalbard reindeer* (HP03) has no evidence that the expected changes have occurred and is hence located in the "no deviation" section of the diagram.

Uncertainties related to the choice of assessment category: There are uncertainties regarding the choice of category. All three indicators have intermediate to good data coverage. The indicator coverage of the ecosystem characteristic, however, is assessed as partially adequate although the set of indicators include the trophic levels in the two dominant food chains: 1) plant—reindeer—Arctic fox (primarily as a scavenger) and 2) plants—geese—Arctic fox (as a predator). This is due partly to the general challenge of formulating indicators which captures the relative changes in biomass distribution among trophic levels. However, the indicator coverage is also limited by the lack of field data on biomass/productivity of relevant food plant/vegetation strata. The plant-related indicators only include satellite-based proxies for plant productivity (see also the ecosystem characteristic *Primary productivity*). Furthermore, while the indicator for the herbivore—predator level includes Svalbard rock ptarmigan, the relationship plants—Svalbard rock ptarmigan is currently not covered, due to the lack of field data on relevant food plants. In the long-term, the assessment can hence be greatly improved by including field data on plant productivity/plant biomass.

High Arctic tundra — Functional groups within trophic levels

Assessment category: Based on one indicator the ecosystem characteristic is assessed as having **no deviation from the reference condition**. This means that the ecosystem characteristic can be considered in good ecological condition.

Justification for choice of assessment category: This assessment is based on only one indicator with one associated phenomenon (HP06 indicator *Hebivorous vertebrates*). Carnivorous vertebrates are not included for High Arctic tundra, because this group is represented by only one functionally important species in Svalbard (i.e. the Arctic fox, which is assessed under another ecosystem characteristic), although polar bears can be a locally significant predator in coastal (manly insular) goose colonies. The phenomenon related to herbivorous vertebrates (HP06) has intermediate validity, mainly due to a less good understanding of how the changes in biomass between different herbivores within the functional group affect ecosystem condition. The changes in species ratios are assessed for Svalbard rock ptarmigan:geese and Svalbard rock ptarmigan:Svalbard reindeer. None of these ratios show any evidence for change, despite that there are large changes in population abundances occurring (EP = None, Fig. 7.3.1b).

Uncertainties related to the choice of assessment category: There are uncertainties related to the choice of category. The assessment is based on just one indicator with very good data coverage. The indicator coverage of the ecosystem characteristic is assessed as inadequate, mainly due to absence of an indicator on plant functional groups.

High Arctic tundra — Functionally important species and biophysical structures

Assessment category: Based on the set of indicators the ecosystem characteristic is assessed as having **limited deviation from the reference condition**. This means that the ecosystem characteristic can be considered in good ecological condition. There is evidence of changes towards a worsened condition with impacts from herbivore grazing on tundra vegetation, but the magnitudes of these changes are such that they are assessed to still have overall limited impact on ecological condition. There are uncertainties related to the choice of category.

Justification for choice of assessment category: This ecosystem characteristic is the most challenging to assess for two reasons. Firstly, the set of six indicators, with six associated phenomena (HP07-HP12) represents a diversity of ecological functions and structures of intermediate (HP12) to high validity (HP07–HP11). For these indicators there are certain links to anthropogenic drivers (although several of the phenomena are linked to a combination of climatic and management drivers) and a good understanding of the indicators' role in the High Arctic ecosystem. Secondly, the phenomena linked to the indicators exhibit a spread on the EP axis ranging from no to intermediate evidence, consequently, yielding assessments of the phenomena in the range of no to substantial deviation from the reference condition. Hence, the overall assessment must consider the relative significance of the phenomena for the overall condition of the ecosystem. For the present ecosystem characteristic to be overall placed in the category "substantial deviation", several phenomena of fundamental implications for the condition the whole ecosystem must be assessed to be in this category. In the present assessment, three of the phenomena are located in the "substantial deviation" of the diagram (HP07, HP08, HP09). Two of these phenomena are related to the increased goose abundance in Svalbard (HP07, HP08). For Barnacle goose (HP08), the species has tripled in population estimates since 1990. Barnacle geese are not hunted and the main anthropogenic driver is climate change which can act both as a positive and a negative driver. Studies of the presence of grazing and goose "grubbing" in High Arctic tundra in Svalbard show increasing presence and extent of this type of grazing. Pink-footed goose (HP07) is one of few indicators supported with data that overlaps the climatic reference period, and the average population today is almost four times higher than the average population during the reference period, despite intensive regulation through hunting. Although, the goose indicators show high level of evidence that the expected changes in population abundance are occurring, the ecosystem significance of the observed changes is still limited. They are not assessed as sufficiently decisive for the overall assessment of the ecosystem characteristic. The phenomenon related to Svalbard reindeer abundance (HP09) shows regional differences in deviation, with an increasing reindeer population in Adventdalen, and a somewhat decreasing reindeer population on Brøggerhalvøya. The remaining phenomena (HP10 *Svalbard reindeer mortality rate*, HP11 *Svalbard reindeer calf rate*, HP12 *Arctic fox abundance*) are located in the "no deviation" section of the diagram, as there is no evidence for changes in the indicators. The fact that these central functions show no evidence of change also supports that the overall assessment of the ecosystem characteristics should be on the conservative side and conclude "limited deviation", despite the observed drastic changes in Arctic goose populations.

<u>Uncertainties related to the choice of assessment category:</u> There are uncertainties related to the choice of category, despite a large set of indicators with intermediate to good data coverage. This is due to the phenomena being spread over all three categories. The indicator coverage of the ecosystem characteristic is assessed as partially adequate, but on the border to inadequate due to the absence of indicators for functionally important plants. There is also a lack of indicators of production of the functionally important goose species.

High Arctic tundra — Landscape-ecological patterns

<u>Assessment category:</u> Based on the set of indicators the ecosystem characteristic is assessed as having **substantial deviation from the reference condition**. This means that the ecosystem characteristic cannot be considered in good ecological condition. This is primarily due to an extensive loss of areas which climatically belong to the coldest Arctic bioclimatic subzone A (Arctic polar desert). There are uncertainties related to the choice of category.

<u>Justification for choice of assessment category:</u> The assessment is based on just two indicators with two associated phenomena (HP13 indicator *Bioclimatic subzones* and HP14 *Wilderness areas*). Both have intermediate validity (VP) with certain links to anthropogenic drivers, but a less good understanding of their role in the High Arctic ecosystem. The phenomenon associated with the indicator *Bioclimatic subzones* (HP13) shows high level of evidence that the expected changes have occurred and high ecosystem significance of observed changes. It is hence located in the "substantial deviation" section of the diagram. Historically (e.g. during the climatic reference period) most of Svalbard was, climatically speaking, located in the coldest High Arctic subzone

(subzone A, Arctic polar desert). This subzone has been strongly reduced and most of Svalbard is today, climatically speaking, located in subzone B (Northern Arctic tundra). Challenges exist with the underlying modelled climate data (see the ecosystem characteristic *Abiotic factors* below, and Appendix 8.2), which are primarily linked to the absolute values for temperature relative to the climatic limits between bioclimatic subzones. However, the relative changes are assumed to be realistic and indicate that most of the High Arctic tundra has climatically approached a new bioclimatic subzone relative to the climatic reference period. This suggest that over time also biotic transitions will occur. Changes in the indicator *Wilderness areas* (HP14) are driven solely by major infrastructure developments and show limited and local reduction in area relative to a reference condition without infrastructure development. The area is almost unchanged over the monitoring period (1990–2019). The phenomenon is hence located in the "limited deviation" section of the diagram. Physical infrastructure development is considered of much lower relevance for the functional and structural integrity of the High Arctic tundra ecosystem than changes in bioclimatic conditions, and the assessment therefore places most emphasis on the phenomenon *Bioclimatic subzones* (HP13) in the overall assessment of the ecosystem characteristic.

<u>Uncertainties related to the choice of assessment category:</u> There are uncertainties related to the choice of category. The assessment is based on just two phenomena which are located in two different categories. The assessment is based on one of these being considered of much higher relevance than the other, and also of better data coverage. The indicator coverage of the ecosystem characteristic is assessed as partially adequate, mainly due to the lack of indicators on erosion and vegetation damage.

High Arctic tundra — Biological diversity

<u>Assessment category:</u> Based on the set of indicators the ecosystem characteristic is assessed as having **no deviation from the reference condition**. This means that the ecosystem characteristic can be considered in good ecological condition. There are uncertainties related to the choice of category.

<u>Justification for choice of assessment category:</u> The assessment is based on just one indicator, with one associated phenomenon (HP15 indicator *Svalbard rock ptarmigan breeding abundance*). The phenomenon is assessed as having intermediate validity (VP) in part due to recent evidence on the role of climatic drivers, particularly a positive effect from increasing winter temperatures on ptarmigan abundances. Hence, there is no evidence of change towards a worsened condition, and the phenomenon is thus located in the "no deviation" section of the diagram.

<u>Uncertainties related to the choice of assessment category:</u> There are uncertainties related to the choice of category, since the assessment is based on just one indicator with very good data coverage. The indicator coverage of the ecosystem characteristic is assessed as inadequate, because of the absence of indicators on important components of High Arctic biodiversity — such as vascular plants, terrestrial birds (other than the ptarmigan) and arthropods.

High Arctic tundra — Abiotic factors

<u>Assessment category:</u> Based on the set of indicators the ecosystem characteristic is assessed as having **substantial deviation from the reference condition**. This means that the ecosystem characteristic cannot be considered in good ecological condition. The observed changes are dramatic and have occurred over the entire High Arctic tundra. Several indicators are close to or exceed the historical observed variation during the reference period, in other words, values which during the 1961–1990 period were considered extreme are now within the expected norm.

Justification for choice of assessment category: The assessment is based on nine indicators, with ten associated phenomena (HP16–HP25). The phenomena have intermediate to high validity (VP) with certain links to anthropogenic drivers and relatively good understanding of their role in the High Arctic ecosystem. Two phenomena (HP16 indicator *Days with extreme cold* and HP22 indicator *Changes in annual precipitation*) are located in the "limited deviation" section of the diagram, and in particular the phenomena related to precipitation score low on the EP axis due to a low level of evidence for change. The remaining eight phenomena related to temperature (HP17 indicator *Winter melt days*, HP18 indicator *Degree days*, HP19 indicator *Growing degree days*, HP20 indicator *Annual mean temperature*, HP21 indicator *July mean temperature*), snow (HP25 indicator *Snow cover duration*) and permafrost (HP23 and HP24) show high levels of evidence that the expected changes in the indicators have occurred and partly high ecosystem significance of observed changes (EP=intermediate to high) and are hence located in the "substantial deviation" section. For High Arctic tundra, the phenomena related to temperature and snow cover are based on current knowledge considered to be of more relevance for ecosystem's condition than phenomena related to precipitation. In addition, the validity of these phenomena is higher (VP = High) than precipitation-related phenomena. Therefore, more emphasis is placed on these phenomena in the assessment of the ecosystem characteristic. The observed changes in temperature are among the most dramatic observed anywhere in the Arctic. For instance, HP20 (*Annual mean temperature*) show a positive rate of change of approximately 1°C /decade since the climatic reference period (1961-1990) and is exceeding the observed 1961-1990 variation. Permafrost temperatures (HP23) have increased by approximately 2°C since the beginning of the monitoring in 1999 and the depth of the active layer (i.e. the layer that thaws during the summer, HP24) has increased by > 30 cm. Such changes will affect the growing conditions of plants (e.g. through temperature, nutrient availability and moisture content), as well as surface stability. The High Arctic tundra is currently on an abiotic change trajectory which over time will not permit the maintenance of structurally and functionally intact High Arctic ecosystems.

Uncertainties related to the choice of assessment category: There are no major uncertainties related to the choice of category. The data coverage of the indicators is very good, except for the indicator *Permafrost* (HP23, HP24) that has intermediate data coverage. The indicator coverage of the ecosystem characteristic is assessed as partially adequate despite a comprehensive set of indicators. This is due to the absence of indicators that characterise regional snow quality, including snow structure, regional extent of basal ice and "rain-on-snow" events, which would allow more direct causal links to be established between abiotic conditions and biotic ecosystem characteristics. Further, albedo, which represents the reflective qualities of the surface in late winter/spring, is another important indicator not included in this assessment, which would allow closer causal links between biotic land surface changes, abiotic conditions (snow cover, snow melt) and regional climate feedbacks (through changes in the reflective properties of the land surface) to be established. In addition, there are limitations associated with the gridded climate data for Svalbard. Due to the sparse weather station network in Svalbard, spatially distributed climate datasets have to rely on atmospheric models forced by global reanalysis data. These models tend to have a cold temperature bias in these regions, and they generally estimate too much precipitation. The spatial resolution is coarse, several kilometres, so the local topography is not resolved in detail. The Sval-Imp dataset (Schuler and Østby 2020) is based on a downscaling of the reanalyses. In the precipitation datasets from Sval-Imp, the modelled estimates are two to three times higher than land-based weather stations in Longyearbyen and Ny-Ålesund (Schuler and Østby 2020). The NORA3 dataset appears less biased, but still has challenges related to a limited temporal coverage.

A typical flat, coastal landscape of High Arctic tundra in Svalbard. The physical proximity and coupling between the terrestrial, marine, glacial, and freshwater ecosystems result in considerable environmental heterogeneity along short gradients. Photo: J.M. Mosbacher/NPI

7.3.2 Assessment of the condition of the ecosystem as a whole

Based on the overall assessment of the seven ecosystem characteristics, the scientific panel concludes that Norwegian Arctic tundra ecosystems — in the High Arctic and the Low Arctic — show limited deviation from the reference condition. Thus, both sub-ecosystems are still in good ecological condition with fundamental structures and functions mainly maintained. The biotic changes that have occurred are mainly driven by climate change, which is happening fast in the Norwegian Arctic. This is evident in the present assessments as substantial changes in the ecosystems' abiotic factors. However, also biotic ecosystem characteristics show deviations from the reference condition that are mainly consistent with phenomena driven by climate change. This regards in particular the Low Arctic sub-ecosystem, which should be considered a warning of more extensive incipient ecosystem changes.

Current state of knowledge of the reference condition

According to the normative description of the reference condition for tundra (Ims et al. 2017b), a Low Arctic tundra ecosystem in good ecological condition should have structures and functions, which to a large extent are determined by a Low Arctic climate, with a primary production that is higher than decomposition leading to a net buildup of carbon. The food webs should be dominated by functional groups, which are defining for Low Arctic ecosystems. Biotic food web interactions should be tied to population peaks of small rodents occurring with a regularity and amplitude that maintain characteristic Low Arctic tundra vegetation types, and Arctic specialist predators. Species communities should not have increasing occurrence or dominance of boreal species. The snow cover should have a depth, structure and morphology that provides suitable conditions for functionally important Low Arctic species and habitats.

Similarly, High Arctic tundra ecosystems in good ecological condition (Ims et al. 2017, Ims et al. 2017b) should have structures and functions which to a large extent are determined by a High Arctic climate, with a primary production that is higher than decomposition leading to a net buildup of carbon, the majority of which is locked in permanently frozen ground. The food webs should be dominated by functional groups which are defining for High Arctic ecosystems, including viable populations of High Arctic species/subspecies endemic to Svalbard. The important nutrient flow to tundra from marine ecosystems should be maintained through large seabird colonies and sea ice, which permits mobility of functionally important carnivores across the marine-terrestrial boundary. Species communities should not have increasing occurrence or dominance of Low Arctic or other alien species.

Keeping these points in mind, the current state of knowledge of the reference condition for Arctic tundra is very good with regard to past and current climatic conditions and the climatic boundaries which define the Arctic biome and the terrestrial bioclimatic subzones within it. The fundamental ecosystem functions and structures, such as the identity of Low and High Arctic ecological communities and their dominant biotic interactions and how they are contingent on a Low and High Arctic climate, are also well known. The current state of knowledge is very good with respect to which species and functional groups can be considered *defining* for Low Arctic and High Arctic ecosystems respectively. This permits us to detect increasing influence or dominance from more southern species. However, we lack to a large extent knowledge on the historical and current quantitative aspects of some fundamental ecosystem processes, such as the relationship between primary production and decomposition, and the relative importance of top-down and bottom-up regulation and various forms of subsidies (natural marine and anthropogenic) on food web dynamics. Such knowledge is crucial, for instance for predicting the precise nature of ecosystem responses (e.g. thresholds or other sorts of non-linearities) to drivers of change.

Main drivers of change

The Arctic tundra ecosystem is fundamentally contingent on the bioclimatic conditions that provide the foundation for species, communities and food webs and their ecological functions and diversity specific to the bioclimatic subzones. Climate change, in particularly increasing temperatures, is expected to be the main driver of ecosystem changes in Arctic tundra ecosystems (ACIA 2004, CAFF 2013, Post et al. 2019, Post et al. 2009). Hence, the condition of the ecosystem characteristic *Abiotic conditions* is to a certain degree a determinant of the current or future condition of many of the defining biotic ecosystem elements. While abiotic indicators may act as drivers on biotic indicators, driver-response relationships may also be the other way around (feedbacks), through biotic processes driving change in abiotic indicators. Browsing by large herbivores, for instance, can influence snow cover distribution and thereby spring albedo (Biuw et al. 2014, Cohen et al. 2013) and temperature. Generally, ecosystem dynamics are to a large degree due to *interactions* between and within the biotic and abiotic compartments of the ecosystems, and ecosystem change is often due to chain reactions (cascades) within and between these compartments resulting from driver impacts (Ims et al. 2013b). This is in line with all the phenomena that the scientific panel has formulated and assessed on the levels of indicators and ecosystem characteristics. At the ecosystem level, the cumulative outcome of these phenomena may lead to ecosystem state transitions between known states. Hence, the high Arctic ecosystem of Svalbard may be climatically forced on a trajectory towards Low Arctic and eventually boreal conditions (Xu et al. 2013). If such ecosystem state changes become realised, the deviation from the reference condition will be substantial and the entire ecosystem must be assessed as in a poor condition. Some state changes are likely to deviate from expectation of the change trajectories that are outlined in terms of the PAEC phenomena, for instance, due to a non-analogous climate, extreme weather events, and surprising disturbances and synergies from multiple drivers (e.g. climate changes and harvest). Climatic abiotic conditions cannot be managed at the scale of the ecosystems, but nevertheless need to be accounted for when assessing the total loads and those drivers which are manageable, such as land use and harvesting. Such manageable ecosystem level drivers may simply add to the total load or may potentially interact synergistically with climate change. In any case, substantial or pervasive deviations in the set of indicators/ecosystem characteristics can provide the basis for assessing whether the ecosystem is in poor condition relative to the reference condition.

Observed deviations from the reference condition

The set of indicators describing the ecosystem characteristic *Abiotic factors* substantially deviates from the reference condition for the Low and High Arctic tundra. All temperature-related indicators show substantial deviation with expected long-term consequences for species-specific life conditions and ecosystem functions in both sub-ecosystems (CAFF 2013). The central *Bioclimatic subzones* indicator, which is based on *July mean temperature*, offers the best prediction for the structure and function of Arctic ecosystems. The *Bioclimatic subzones* indicator shows substantial deviation leading to the same overall deviation in the ecosystem characteristics *Landscape-ecological patterns* in the Low Arctic and the High Arctic. In the Low Arctic, an entire bioclimatic subzone has vanished, in the sense that areas which during the reference period corresponded to the climatic definition of the coldest Low Arctic subzone (subzone D), now climatically correspond to the warmest Low Arctic subzone (subzone E), while areas previously located within the climatic definition of subzone E now are warmer than this (e.g. boreal). Similar shifts in bioclimatic subzones are also occurring in the High Arctic, but methodical challenges associated with the modelled climate data make it more challenging to estimate the area loss of High Arctic subzones. However, the rates of change in abiotic conditions in the High Arctic are more dramatic than in the Low Arctic. For instance, the indicator *Mean annual temperature* suggests a rate of change since the climatic reference period of around or above 1°C/decade for the High Arctic, which is almost twice the estimate for the Low Arctic.

Several biotic changes affecting the condition of the ecosystem are expected to occur based on the observed changes in bioclimatic zonation. The Low Arctic tundra has continuous ecotones (borders) towards alpine and boreal systems, while the High Arctic tundra in Svalbard is isolated by ocean and hence lacks a Low Arctic ecotone. Spread and establishment of boreal elements in the Low Arctic tundra ecosystem can hence be expected to occur at a faster rate than the equivalent spread of Low Arctic elements into the High Arctic tundra ecosystem in Svalbard. This is in accordance with the observed changes in this assessment, where several biotic characteristics in the Low Arctic ecosystem show more substantial deviations from the reference condition than their High Arctic counterparts. However, it should be noted that the indicator coverage of several of the ecosystem characteristics is poorer in the High Arctic than in the Low Arctic (Table 7.3.2a,b).

The ecosystem characteristic *Primary productivity* is predicted to increase. Accordingly, Low Arctic and High Arctic tundra show a significant tendency for greening. However, this tendency is spatial heterogeneous and area restricted. Hence, the changes in *Primary productivity* are assessed as still limited, which is in accordance to experimentally demonstrated time-lagged tundra vegetation response to warming (Elmendorf et al. 2012, Elmendorf et al. 2015). Simultaneous opposing changes in winter climate can counteract the increase in primary production, for instance through winter damage to the vegetation causing browning in the Low Arctic and High Arctic tundra. In the Low Arctic tundra-forest ecotone, the remotely sensed signals of browning are likely due to immediate impacts of spreading geometrid moth outbreaks, a driver of change currently not present in the High Arctic. The deviations found in *Functionally important species and biophysical structures* are in accordance with phenomena linked to climate change, but mostly limited. However, some of the deviations are deemed substantial and thus deserve attention. Especially the Low Arctic tundra-forest ecotone is substantially impacted by outbreaks of geometrid moths leading to reduction of forested areas and cascading negative effects on other functionally important species such as willow ptarmigan. Also, the linked spread of geometrids in the adjacent shrub tundra needs further attention as an indication of potential incipient state changes in the low Arctic. Attention should be paid to some of the indicators/phenomena of *Functionally important species and biophysical structures* because they are related to management. In the Low Arctic, this regards for instance red fox and large carnivores because of their important functions as predators, and large herbivores (reindeer) based on their central position in the food web. In the High Arctic, the large increase in abundance of medium herbivores (geese) should be in focus, although grazing impacts are still deemed to be of limited ecosystem significance.

The ecosystem characteristic *Biological diversity* is assessed as having substantial deviation in the Low Arctic tundra. This assessment is partly due to the status of single species, such as the Arctic fox and snowy owl that are endemics to Arctic regions and/or red-listed, or the rapidly vanishing diversity of bird communities that characterise the Low Arctic tundra. These indicators are not representative of the biological diversity in the entire ecosystem, which emphasises the need of giving this ecosystem characteristic a better indicator coverage. At the same time, these indicators represent typical Arctic species that are high in the food web (i.e. carnivores and insectivores) and sensitive to changes (e.g. indirect effects due to trophic cascades), especially at the edges of their distribution ranges. Changes in their abundance or demography can therefore be early warnings of incipient ecosystem state changes. The comprehensive Low Arctic bird community indicator shows that a proportion of open tundra species declines fast — a decline consistent with recent finding in alpine ecosystems in Fennoscandia (Lehikoinen et al. 2019, Lehikoinen et al. 2014). The poor indicator coverage of *Biological diversity* in High Arctic Svalbard (with presently only one species included) should be noted.

The presence of breeding snowy owls in the Low Arctic tundra is closely linked to regularly occurring lemming peak years. The Low Arctic part of Finnmark has historically been assumed to be one of the most important breeding grounds for snowy owl in Norway. Absence of breeding pairs of snowy owl during lemming peaks is considered of ecosystem significance regardless of cause. Photo: K.-O. Jacobsen©/NINA

Table 7.3.2a. Graphical summary of the assessment of ecological condition for all ecosystem characteristics in Low Arctic tundra.

Ecosystem characteristic	Deviation from reference condition			Indicator coverage		
	No	*Limited*	*Substantial*	*Inadequate*	*Partially adequate*	*Adequate*
Primary productivity		●			●	
Biomass distribution among trophic levels		●			●	
Functional groups within trophic levels		●				●
Functionally important species and biophysical structures		●			●	
Landscape-ecological patterns			●		●	
Biological diversity			●		●	
Abiotic factors			●		●	

Table 7.3.2b. Graphical summary of the assessment of ecological condition for all ecosystem characteristics in High Arctic tundra.

Ecosystem characteristic	Deviation from reference condition			Indicator coverage		
	No	*Limited*	*Substantial*	*Inadequate*	*Partially adequate*	*Adequate*
Primary productivity		●		●		
Biomass distribution among trophic levels		●			●	
Functional groups within trophic levels	●			●		
Functionally important species and biophysical structures		●			●	
Landscape-ecological patterns			●		●	
Biological diversity	●			●		
Abiotic factors			●		●	

7.3.3 Future trajectories for ecosystem condition

The pace of climate change is currently rapid in the Norwegian Arctic. The rate of change in the bioclimatic decisive indicator, *July mean temperature,* in the three decades after the climate reference period has been in the range of -0.2–0.7°C/decade in the low Arctic and 0.3–1.1°C/decade in the High Arctic. Similarly, snow cover duration in the Low Arctic tundra has decreased in the order of three weeks over the last three decades. In the High Arctic tundra, permafrost temperatures have increased by close to 1.0°C/decade since the monitoring was initiated. If this current pace of change continues, which is likely (Hanssen-Bauer et al. 2019, Hanssen-Bauer et al. 2015, IPCC 2020), both of the tundra sub-ecosystems subjected to the present assessment will in a few decades be far beyond the climate envelopes of their reference conditions. Hence, High Arctic Svalbard may soon be situated in a boreal bioclimate, while Low Arctic Finnmark may be in nemoral bioclimate. While we can expect the ecosystem significance of such vast changes to be immense in terms of fundamental state changes that certainly involve loss of Arctic ecosystem functions and biodiversity, predicting which future ecosystem states that will emerge in the long-term is not within reach. This is because ecosystems subjected to strong driver pressures are likely to show a mixture of fast and slow (time-lagged) responses in the state variables (Williams et al. 2021). Some responses will be highly non-linear or strongly interacting in a manner that can cause surprising overall state shifts or long-term transient states (CAFF 2013, Hastings et al. 2018, Ims and Yoccoz 2017, Lindenmayer et al. 2011, Planque 2016). The highly ecological significant perturbation caused by spreading geometrid moth outbreaks of the forest-tundra ecotone in Finnmark, and the incipient spread of the same disturbance in the Low Arctic shrub tundra, provide illustrative examples of such surprises.

Despite these limitations, PAEC provides means for predicting future ecosystem conditions on a short time horizon. This is because the phenomenon specified for each indicator represents qualitative predictions of near-term trajectories of change. These predictions are empirically validated, and if necessary updated, by statistical analysis of monitoring time series data during each PAEC assessment. Hence, all phenomena that have received statistical support in the present assessment represent also valid prediction towards the next PAEC. Collectively, the empirically supported phenomena in this assessment demonstrate that the Low Arctic Finnmark is presently subjected to a rapid borealisation of the ecosystem.

The statistical time series analyses yield rate-of-change estimates that in principle can be used for quantitative extrapolation in terms of future trajectories and states of the indicators. For instance, with the current rate of reduction in the bioclimatic tundra zone E, this zone will be lost within the year 2030 in eastern Finnmark. We recommend however, that quantitative prediction of near-term future trajectories and states should be based on statistical models of driver-response relations. Such models can derive predictions for state variable as influenced by the action of multiple drivers (Henden et al. 2020, Marolla et al. 2021). Multi-driver models may be especially useful for predicting and validating how management interventions may modify trajectories resulting from climate change. Such models can thereby aid to develop management strategies aimed to mitigate what is considered a deteriorated ecological condition.

7.3.4 Recommendations for monitoring and research

The current assessment of tundra is based on a set of selected indicators derived from the COAT — *Climate-ecological Observatory for Arctic Tundra* (Ims et al. 2013a) that for Svalbard forms a large part of the terrestrial *Environmental Monitoring of Svalbard and Jan Mayen* (MOSJ 2020), in addition to indicators derived from METs national data services and other national data bases (see Table 3.2a, b). During the assessment, the scientific panel further identified focal components of Arctic food webs, not covered by the current set of indicators, but which are recommended for inclusion in the next assessment (7 for Low Arctic, 10 for High Arctic; Table 7.3 a, b). It will require predictable funding to ecosystem-based, adaptive monitoring programmes to allow the continuation of established time series, and the development of new essential indicators. Such funding is currently lacking. Alongside this, more model-based quantitative analyses on the causal links between ecosystem indicators and stressors is needed to improve our understanding of the implications of changes in indicators for ecosystem condition, especially in cases when the same structures and/or functions are simultaneously impacted by multiple stressors. This effort to improve the validity of assessments should be guided by the best empirical knowledge that are formulated as hypotheses on drivers, ecosystem processes and trends (CAFF 2013). A PAEC assessment is centred on such hypotheses in the form of the phenomena.

Currently we entirely lack data to permit indicators on pollinating insects and decomposers to be included in the assessment of Low and High Arctic tundra. Both are focal components within all bioclimatic zones of the Arctic tundra biome (Gillespie et al. 2020). Particularly, decomposition is such a central function of boreal and Arctic ecosystems, for instance as a determinant of ecosystem carbon budget (Xu and Shang 2016) that it could be considered as an unfortunate omission that it was not included among the ecosystem characteristics in Nybø and Evju (2017). At present, there are no systematic time series of pollinating insects and decomposers in the Norwegian terrestrial Arctic. This "state of affairs" is probably more due to lack of financial resources to monitor such indicators than lack of interest and competence in the community of Arctic ecologists.

Several of the indicators already included in this assessment can be improved using new technology; for example, monitoring of herbivores and predators using cameras, acoustic monitoring of bird communities, and drone and satellite monitoring of vegetation. Such technology will increase the scope of field measurements by including more spatial strata and larger parts of the ecosystem, as well as giving several of the indicators a better temporally coverage and spatial resolution. Making full use of such technology also requires development of analytical methods, in particular statistical models that can integrate data sources with varying spatial and temporal resolutions (Zipkin et al. 2021). COAT Tools make currently substantial efforts to implement and validate this new technology (COAT Tools 2020).

This assessment and other current studies using data derived from COAT (e.g. Kleiven et al. 2018, Ravolainen et al. 2014, Soininen et al. 2018) have demonstrated that several of the field-based indicators show large variation in time and space, which can challenge interpretation of the ecological condition at ecosystem level. This is especially true in cases where the spatial scope of the measurements is limited or where there are no validated models as basis for spatial extrapolations. Even for abiotic indicators with fundamental significance for the condition of Arctic tundra ecosystems (e.g. snow and basal ice), correlations between field measurements and model extrapolated values are still poor (see Peeters et al. 2019). Therefore, it is essential to develop improved physical/statistical models for several of the abiotic indicators. This presupposes that extended networks of ground-based sensors — especially weather stations as implemented in COAT along climate-ecological relevant gradients — are established as a basis for model development.

There is presently a relatively good understanding of the links between remote sensed indicators, such as vegetation productivity, and drivers (especially climate). In addition, the ecological significance of changes in these indicators for their respective ecosystem characteristics is relatively well known (i.e. changed growing conditions; Beck and Goetz 2011, Vickers et al. 2016), intensification of insect outbreaks (Jepsen et al. 2009b). However, most of the ecosystem characteristics must be assessed based on field-based monitoring and an understanding of total loads from multiple stressors and impacts on these characteristics. The assessment of total loads on ecosystems, which is mandated under the *Norwegian Nature Diversity Act* (Lovdata 2021), requires analyses of quantitative ecosystem models. Significant advances in such modelling of direct relevance to PAEC, as well as for the development of management strategies and objectives, have recently been made in COAT and the related research project SUSTAIN (Mellard et al. 2021, see also Pedersen et al. 2021). Further developments are however needed to build more comprehensive ecosystem models (Geary et al. 2020) that, for instance, can lead to more interpretable indicators of complex ecosystem characteristics such as food web and community structure (e.g. *Distribution among trophic levels* and *Functional groups within trophic levels*) and for indicators where it is challenging to acquire reference data (e.g. plant growth forms and plant diversity). For ecosystems that are undergoing fundamental and rapid changes, as is now happening in the Norwegian Arctic tundra (Hanssen-Bauer et al. 2019, Hanssen-Bauer et al. 2015), there is a strong need for continuous development work to keep up with the emerging challenges. As the ecosystems change, there will be a need for phasing in new, improved indicators and models. This requires adaptive protocols for both the ecosystem-based monitoring system that will provide indicator data, such as COAT, and the methodologies used to make the assessments based on the indicators.

Arthropods, including pollinating insects, are declining worldwide. In the Arctic, terrestrial monitoring of insects is rare. At present no monitoring is in place to capture trends in insect abundance and diversity for neither Low nor High Arctic tundra in Norway. Currently, new methods using camera-traps are tested in both regions, and thus recommended for inclusion in the next assessment. Photos: J. Jepsen/NINA

Table 7.3.4a. Indicators for Low Arctic tundra, which are not included in this assessment, but which could be operationalised and, thus, recommended for inclusion in the next assessment of Low Arctic tundra according to the PAEC protocol. For recommendations on further development of indicators included in the assessment, see Appendices 8.1 and 8.2.

Ecosystem characteristic	Indicator	Description of the indicator role for the ecosystem characteristics
Biological diversity	Bird communities — TOV-E	There is a documented decrease in abundance of Arctic and alpine bird communities in Scandinavia after 2000 (Lehikoinen et al. 2014). Monitoring of tundra bird communities, associated with willow thickets on Varanger Peninsula, corresponds with this finding (see indicator *Bird communities*). *Extensive monitoring of breeding birds (TOV-E)* is the most comprehensive monitoring programme for terrestrial birds in Norway, and TOV-E delivers status and trends for Norwegian bird species to a number of national and international fora including the *Pan European Common Bird Monitoring Schemes* (PECBMS 2021) and the UNEP–World Conservation Monitoring Centre (Kålås et al. 2020). Sampling in TOV-E is based on a coarse (18×18 km) systematic grid, and includes approx. 500 monitoring quadrats in the whole country. Only a small number of these are located in Low Arctic tundra and the bordering forest ecotone. Some of these are recently established and hence for the time being provide limited possibility for assessing trends and changes in ecological condition over time. We consider the existing indicator on bird communities (including recommended methodological developments), better suited for assessing the effects of relevant drivers on tundra bird communities, since it is based on a sampling design which specifically includes such drivers. However, for ecosystem-level assessments of ecological condition, it is of interest to evaluate to what extent the TOV-E data from eastern Finnmark could provide information on trends in abundance and community composition across ecosystems and bioclimatic regions, relative to such based on more intensive monitoring targeted towards specific habitats and/or effects of specific drivers. We hence recommend assessing whether a regional scale indicator on bird communities (abundance, species composition) based on TOV-E monitoring quadrats within and bordering upon the Low Arctic tundra regions in eastern Finnmark could provide robust trend estimates.
Functionally important species and biophysical structures	Insect communities in dead wood after outbreaks	Insect outbreaks in the forest-tundra ecotone result in a strong pulse of dead wood into the ecosystem over very short time. Further south, the community of insects associated with dead wood habitats plays an important functional role as a decomposer (Jacobsen et al. 2018b). The abundance and composition of functional groups in the insect community have relevance for the rate of decomposition, that historically has been low in the forest-tundra ecotone due to cold climate. Thus, in a warmer climate, changes in the abundance and functional composition of the insect community can be expected to have consequences for the decomposition of dead wood in the forest-tundra. The COAT monitoring of beetle communities associated with dead wood, which has been ongoing since 2011, is to our knowledge the only data that document changes in composition of the insect community and its response to amount of dead wood in the northern birch forest (Vindstad et al. 2014). This time series can be used to develop an indicator for insect communities associated with dead wood, although many additional years of data may be needed to distinguish long-term trends from the large natural fluctuations that occur in many species.
	Large raptors	The *Terrestrial Expert Monitoring Group* (TEMG) of the *Circumpolar Biodiversity Monitoring Program* (CBMP) identified large raptors, in particular the peregrine falcon (*Falco peregrinus*) and the gyrfalcon (*Falco rusticolus*) as "*Focal Ecosystem Components*" due to their positions as top predators within Arctic food webs (Franke et al. 2020). In particular, the gyrfalcon is an important indicator relative to a food chain where ptarmigan spp. are key herbivores (i.e. functionally important species). The gyrfalcon is a specialist ptarmigan predator. Moreover, the gyrfalcon's geographic range is primarily within the Arctic tundra biome and, hence, it qualifies as an indicator of Arctic biodiversity.

Table 7.3.4a. Continued

Ecosystem characteristic	Indicator	Description of the indicator role for the ecosystem characteristics
Functionally important species and biophysical structures (continued)	Large raptors (continued)	Supported by funding from the Norwegian Environment Agency (NEA), COAT has recently mapped the breeding sites of the gyrfalcon on Varanger Peninsula and has established a protocol for annual monitoring of these sites (Østlyngen et al. in prep.). Data from two years' monitoring (2019 and 2020) have been gathered. Pending further support from to NEA to this monitoring the gyrfalcon breeding population and success will be entered as Low Arctic indicators of the ecosystem characteristic *Biological diversity* in PAEC. As the large raptor monitoring also includes nesting sites of golden eagles (*Aquila chrysaetos*), this raptor might be considered as an indicator for the next PAEC.
	Mountain birch in tundra	The large ongoing changes in abiotic conditions (i.e. growing conditions) are expected to result in increasing establishment of shrubs and trees in tundra landscapes (see climatic forest/tree line below). The resulting encroachment and increase in productivity of tundra landscapes will have a range of implications for tundra ecosystems (e.g. Ims et al. 2019), and eventually for regional climate feedbacks (Swann et al. 2010). A regional indicator of the occurrence of trees and shrubs (primarily mountain birch) in tundra, based on remote-sensing data (aerial images, and satellite data), supplemented by field data for validation, will reflect these changes.
	Pollinators	Increased scientific knowledge about trends in pollinating species is a central goal of the *National Pollinator Strategy for Norway* (Norwegian Ministries 2018). Arthropods, including pollinating insects, are declining, in some cases drastically (Hallmann et al. 2017, Seibold et al. 2019, Wagner et al. 2021). Declines have also been reported from Arctic ecosystems with little anthropogenic influence other than climate change (Høye et al. 2021, Høye et al. 2013). However, terrestrial monitoring of insects is rare and typically suffer from substantial taxonomic bias towards groups such as butterflies, beetles and wild bees. In Arctic tundra the functionally most important group of pollinators are muscid flies (Tiusanen et al. 2016). No monitoring is in place to capture changes in trends in insect abundance and diversity for neither Low or High Arctic tundra in Norway, and it is hence unknown whether these insects show similar declining trends as have been observed elsewhere. During the last few years however, new methods of detailed camera-based monitoring of pollinators have been developed (Høye et al. 2021b) and tested on several Arctic tundra sites, including Varanger and Svalbard. Methodologically these methods are at a stage where they can be operationalised, and they likely give new possibilities for not just monitoring pollinator abundances and diversity, but also for quantifying their role as pollinators because the frequency of visits by insects to flower heads are observed directly. We recommend including a camera-based indicator on pollinators, particularly focusing on their functional role.
Landscape-ecological patterns	Climatic forest/tree line	The bioclimatic subzones defined by CAVM (CAVM Team 2003) are useful for large scale land cover delineations, but since they are based on circumpolar thresholds, they are of limited use for e.g. monitoring of changes in growing conditions for trees and shrubs and hence the potential for woody encroachment in tundra. For the time being there is ongoing development work on locally downscaled, modelled climate data for the Norwegian low Arctic tundra region within COAT. Based on this, it will be possible to make local calculations of changes in climatic thresholds for forest and shrub zones (Bryn and Potthoff 2018, Korner 2007) that have higher relevance for assessments of the condition of the tundra ecosystem than for instance the southern delineation of the low Arctic CAVM subzones.
Abiotic conditions	Albedo	Albedo is governed by snow cover and characteristics of the vegetation cover, especially distribution of shrubs and trees, and has an important regulating function in the climate system. Warming-induced reductions in the duration and extent of Arctic spring snow cover, lower the albedo because snow-free land reflects much less solar radiation than snow (Meredith et al. 2019). Herbivore effects, particularly reindeer grazing, can influence albedo via their effect on shrubs and trees in the forest-tundra ecotone and shrub tundra (Biuw et al. 2014, Cohen et al. 2013). It is recommended to include a regional indicator on albedo, based on MODIS (2000 until present).

Table 7.3.4b. Indicators for High Arctic tundra, which are not included in this assessment, but which will be operational and, thus, recommended for the next assessment of High Arctic tundra according to the PAEC protocol. For recommendations on further development of indicators included in the assessment, see Appendices 8.1 and 8.2.

Ecosystem characteristic	Indicator	Description of the indicator role for the ecosystem characteristics
Functionally important species and biophysical structures	Pink-footed goose production	Data are available on production of young (proportion of juveniles in autumn population and family sizes) from 1980 until present for the Svalbard breeding pink-footed goose population (Heldbjerg et al. 2020). Surveys of numbers of nests and nest fate of pink footed geese in Sassendalen have been conducted since 2003 (with few gaps; conducted after hatching, i.e. with no disturbance effects) and can be related to onset of spring, predation and abundance of Arctic foxes, and effects on vegetation. At present, camera-based monitoring of breeding success for pink-footed geese, in order to investigate the implications of earlier onset of spring on breeding success, is under development. These data will be important in supplementing abundance data and it is recommended to develop an indicator specific to production in pink-footed goose. Corresponding data do not exist for barnacle goose.
Functionally important species and biophysical structures	Arctic fox zoonoses	Arctic fox is the major vector for rabies in the Arctic and the determinant host of the tape worm *Echinococcus multilocularis* (Fuglei et al. 2008, Mørk et al. 2011). Both of these zoonotic disease agents impact the Arctic fox population negatively. Monitoring data for the state of the zoonoses of the Arctic fox exist from 1997 until today. COAT established monitoring of the intermediate host of the tape worm, the sibling vole (introduced and alien listed species), using photo boxes in 2019–2020. This allows for monitoring of the distribution and dispersal of the sibling vole and, thus, development of an indicator on spreading of the tape worm.
Functional groups within trophic levels	Plant growth forms	Abundance of plant growth forms is of great significance to herbivore populations, nutrient cycling and primary production. Abundance of plant growth forms is expected to change with climate change and populations of herbivores (Ravolainen et al. 2020). There is a local time-series from 1996 until present (van der Wal and Stien 2014) and spatially replicated dataset in COAT, the latter being newly established (2019 onwards). We recommend these data sources to be used to establish an indicator for functional groups of important plant growth forms, as well as compiling older data in search for historical descriptions of plant growth form abundance as a reference condition.
	Pollinators	Increased scientific knowledge about trends in pollinating species is a central goal of the *National Pollinator Strategy for Norway* (Norwegian Ministries 2018). Arthropods, including pollinating insects, are declining, in some cases drastically (Hallmann et al. 2017, Seibold et al. 2019, Wagner et al. 2021), and declines have also been reported from Arctic ecosystems with little anthropogenic influence other than climate change (Høye et al. 2021, Høye et al. 2013). However, terrestrial monitoring of insects is rare and typically suffer from substantial taxonomic bias towards groups such as butterflies, beetles and wild bees. In Arctic tundra the functionally most important group of pollinators are muscid flies (Tiusanen et al. 2016). No monitoring is in place to capture changes in trends in insect abundance and diversity for neither Low or High Arctic tundra in Norway, and it is hence unknown whether these insects show similar declining trends as have been observed elsewhere. During the last few years however, new methods of detailed camera-based monitoring of pollinators have been developed (Høye et al. 2021b) and tested on several Arctic tundra sites, including Varanger and Svalbard. Methodologically these methods are at a stage where they can be operationalised, and they likely give new possibilities for not just monitoring pollinator abundances and diversity, but also for quantifying their role as pollinators because the frequency of visits by insects to flower heads are observed directly. We recommend including a camera-based indicator on pollinators, particularly focusing on their functional role.

Table 7.3.4b. Continued

Ecosystem characteristic	Indicator	Description of the indicator role for the ecosystem characteristics
Landscape-ecological patterns	Vegetation cover	Vegetation cover is of importance to herbivore populations and for rates of decomposition and nutrient cycling. Increasing occurrence of processes related to thawing permafrost that disturb vegetation cover (AMAP 2017, Cannone et al. 2010, Cassidy et al. 2017) is expected with increasing active layer depth. Increasing abundance of geese can locally cause erosion of vegetation cover. Extreme climate events are expected to increase damage to vegetation (Ravolainen et al. 2020). There is ongoing work to establish remotely sensed indicators for vegetation cover in COAT (drone and satellite imagery) and in SIOS, that will have data relevant to the assessment of High Arctic tundra. It is recommended to develop an indicator on vegetation cover changes with particular focus on disturbance processes caused by climate change.
Biological diversity	Svalbard rock ptarmigan production	Detailed data on production (i.e. number of juveniles generated by aged wing samples collected from the hunt) of Svalbard rock ptarmigan exist from 1997 until present (Soininen et al. 2016). At present, the estimated reproduction, based on wing samples, is compared to autumn line transect reproduction estimates to assess uncertainties in estimate (Fuglei et al. 2019b). The work is ongoing and this indicator will be an important supplement to the indicator *Svalbard rock ptarmigan breeding abundance.*
	Plant diversity	Composition of vegetation has many implications for the ecosystem. Changes can happen in distribution and abundance of the species existing in Svalbard (Ravolainen et al. 2020, Voldstad et al. 2020) or by introduction of, or increased abundance of, species that have their main distribution elsewhere in the Arctic tundra (Alsos et al. 2007). It is recommended to investigate what data sources exist and to develop an indicator on plant diversity in the High Arctic tundra.
Abiotic conditions	Precipitation/ soil moisture during the growing season	Alongside higher temperature, soil moisture is one of the most important abiotic factors regulating plant species and functional group composition and abundance of plant growth forms (Elmendorf et al. 2012). In a changed climate, moisture can change due to altered precipitation or to increased active layer depth and hence hydrology in the tundra surface (Teufel and Sushama 2019). Development of a regional indicator on precipitation/moisture characteristics during the growing season, based on remote-sensed data and data from climate stations in COAT, is thus recommended.
	January mean temperature	Arctic warming occurs more rapidly in the Arctic than at lower latitudes, and this difference (i.e. Arctic amplification; Serreze and Barry 2011) is more pronounced during the cold season than during the warm season (Box et al. 2019). The indicator *January mean temperature* was not included due to inconsistencies with the gridded datasets. We recommend including this indicator based on development of improved, quality assured gridded data for the High Arctic.
	Albedo	Albedo is governed by snow cover and characteristics of the vegetation cover, especially distribution of shrubs and trees, and has an important regulating function in the climate system. Warming-induced reductions in the duration and extent of Arctic spring snow cover lower the albedo because snow-free land reflects much less solar radiation than snow. The corresponding increase in net radiation absorption at the surface provides a positive feedback to global temperatures. Changes in snow cover dominate land surface related positive feedbacks to atmospheric heating, but regional variations in surface albedo are also influenced by vegetation (Meredith et al. 2019). It is recommended to include a regional indicator on albedo, based on MODIS (2000 until present). Ground monitoring stations for radiation and albedo have recently been established (three stations established and four stations to be established in 2021/2022) by COAT in Svalbard, which over time could provide field-based data for e.g. in-situ long-term changes in albedo and evaluating a remote-sensing based indicator.

Table 7.3.4b. Continued

Ecosystem characteristic	Indicator	Description of the indicator role for the ecosystem characteristics
Abiotic conditions (continued)	Basal ice	Basal ice as a consequence of mild, rainy winters is increasing in the High Arctic Svalbard (Peeters et al. 2019). Such conditions severely block foraging resources and act as a synchronising agent across the vertebrate community in Svalbard (Hansen et al. 2013). The quality of satellite and model-based data is at present inadequate for estimating the spatial extent of basal ice in Svalbard, and only field-based data on local scales exist (see Peeters et al. 2019). Development of an indicator on basal ice will be important to e.g. interpret the populations fluctuations of Svalbard reindeer (Hansen et al. 2019a, Hansen et al. 2019b). At present, MOSJ is developing an indicator on "rain-on-snow", which will be an important supplement to an indicator on basal ice.

8. Appendices

8.1 Scientific basis for indicators — Low Arctic

https://api.npolar.no/publication/64ed5adb-9ee1-49ef-a492-864bc8321080/_file/fecc3621c1a5dbf4d7747cb0b1b80a53

8.2 Scientific basis for indicators — High Arctic

https://api.npolar.no/publication/64ed5adb-9ee1-49ef-a492-864bc8321080/_file/d4d97aff356c5a414b104b69accabaee

8.3 Endnotes to Table 7.1

https://api.npolar.no/publication/64ed5adb-9ee1-49ef-a492-864bc8321080/_file/cfda1cf7e65a60b4b6a6225b9f10d58e

8.4 List of species names

https://api.npolar.no/publication/64ed5adb-9ee1-49ef-a492-864bc8321080/_file/1d032243d98442bf91289ab150aafd29

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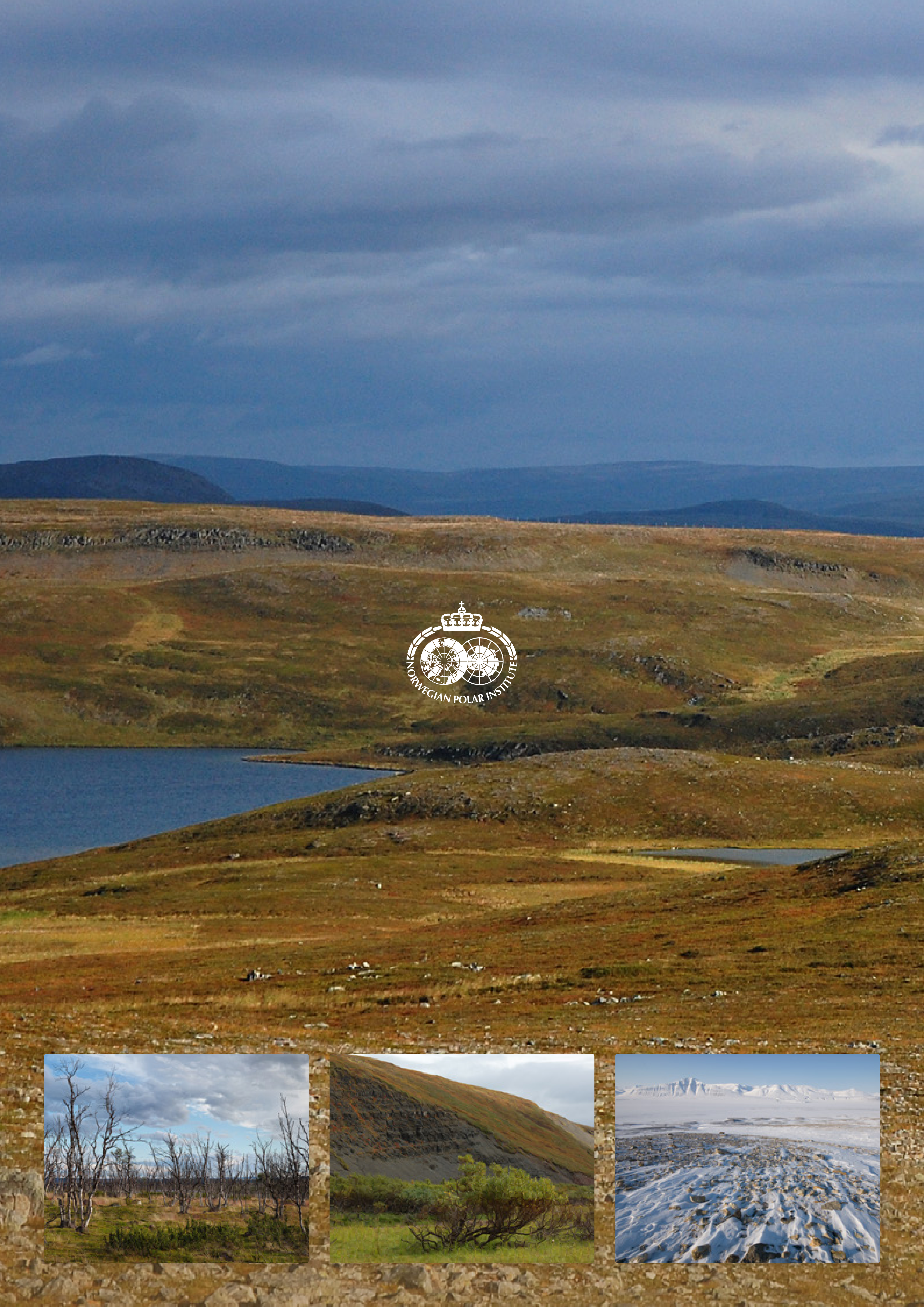
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