056 KORTRAPPORT · BRIEF REPORT

NORSK·POLARINSTITUTT

Panel-based Assessment of Ecosystem Condition (PAEC)

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

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Kortrapport / Brief Report 056

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Photos: E. Eischeid/NPI (main cover photo)
R. Eidesen/UNIS, Jacob, K.-O. Jacobsen©/NINA, J. Iglhaut/NINA (small photos from left to right front cover)
F. Sletten/NPI, L.E. Støvern/UiT, T. Nordstad/NPI (small photos from left to right back cover)

Technical editor: G. S. Jaklin, Norwegian Polar Institute
Print: Bodoni AS

ISSN: 2464-1308 (digital edition)
ISBN: 978-82-7666-443-0 (digital edition)
M-1988 I 2021

Preface

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 2020, the Norwegian Environment Agency commissioned 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. Furthermore, the Norwegian Environment Agency asked us in this brief report to: 1) summarise the process, results and conclusions from the first operational PAEC of Norwegian Arctic tundra (Pedersen et al. 2021), 2) identify and analyse drivers of ecological condition and 3) discuss and exemplify how to use PAEC as a knowledge platform for setting ecosystem-based management objectives for Norwegian Arctic tundra.

The PAEC of Arctic tundra involved 21 experts from five institutions — Norwegian Polar Institute (NPI), Norwegian Institute for Nature Research (NINA), Norwegian Meteorological Institute (MET), The Arctic University of Norway (UiT) and Aarhus University (AU). The work with this report was carried out under the leadership of Åshild Ønvik Pedersen (NPI), in close cooperation with selected experts; Eva Fuglei, Jesper B. Mosbacher, Virve Ravolainen and Ellen Øseth (NPI), Jane U. Jepsen (NINA), Rolf Anker Ims and Nigel Yoccoz (UiT) and Per Arneberg (Institute of Marine Research). Øseth had an administrative role in the scientific panel and acted as a secretary during the assessment phase, and participated in writing this report, particularly chapter 4. Ingrid M. G. Paulsen (NPI) was engaged to assist the 10-month long process as full-time secretary.

Covid-19 restrictions influenced the entire project period, and due to such restrictions, there were no physical meetings involving the entire author group of this report. Instead, several, mostly digital, meetings involving smaller sections of the panel were held.

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 9 April 2021

Åshild Ønvik Pedersen
Project leader

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Summary

The *System for Assessment of Ecological Condition* will provide assessments of the condition for each of the nation's major terrestrial and marine ecosystems not covered by the EU Water Framework Directive. Two assessment methods have been developed, and are currently in use in the first operational, full scale assessments of forest, alpine, Arctic tundra and marine ecosystems (Jakobsson et al. 2021, Jepsen et al. 2020). The *System for Assessment of Ecological Condition* is also envisaged to form a basis for devising management plans and setting and evaluating management objectives for Norwegian ecosystems, according to the ambitious policy goals for ecosystem-based management as grounded in legislation.

The assessment of Arctic tundra has been performed by a broad scientific panel according to the *Panel-based Assessment of Ecosystem Condition* method. The assessment, reported in its entirety in Pedersen et al. (2021), is summarised in this report. Based on a set of 24 indicators for High Arctic tundra and 42 indicators for Low Arctic tundra, the scientific panel concludes that: 1) The abiotic compartments of Arctic tundra ecosystems have undergone significant changes in the form of generally increasing surface temperatures, longer and warmer growing seasons, shortening of the snow-covered season and increasing permafrost temperatures, 2) The biotic implications of these abiotic changes are still mostly limited, and mainly evident in ecosystem characteristics and indicators with strong causal links to climate, 3) The fundamental structures, functions and productivity in Norwegian tundra ecosystems are still mainly maintained, so that both sub-ecosystems are classified as being in a "good condition", 4) Some biotic components are presently on significant change trajectories, especially in the Low Arctic, which should be considered a warning of more extensive, incipient ecosystem changes.

Norwegian Arctic tundra is divided into two subsystems — the Low Arctic tundra, located on the Norwegian mainland (this panel), and the High Arctic tundra in Svalbard. Photo: J. Iglhaut/NINA

Assessments of ecological condition and ecosystem-based management both require a focus on separating manageable, as well as non-manageable, stressors from natural variation. Consequently, a strong assessment method should establish routines for the identification and quantification of causal driver–response relations. Identification of these relations is also a presumption to understand what a change in an indicator indicates. Overall, the most effective paradigm for progress in such investigations is one where driver–response relations are formulated as ecological hypotheses. PAEC does this in the form of *phenomena*, which are qualitative expectations of directional change in indicators as a result of relevant drivers. In some cases, there will be a clear expected relation between driver and indicator, thus giving the phenomenon high validity. In other cases, the outcome of multi-driver relations can create complex responses partially or in the entire ecosystem. This results in phenomena of low *validity* according to PAEC, which means that the ecological significance of these multi-driver relations is not well documented nor understood. Statistical modelling can strengthen the validity of such phenomena, but only if adequate monitoring data are available. We exemplify several such models of complex multi-driver relations linked to tundra phenomena that recently have been developed and analysed in the context of COAT — *Climate-ecological Observatory of Arctic Tundra.*

Climate change, which currently overrides all other drivers in the terrestrial Arctic, poses a substantial challenge as a non-manageable driver on an ecosystem level. For an ecosystem, which is rapidly leaving its defining bio-climatic envelope, it is also difficult to set concrete, attainable management objectives. We propose that it is necessary to develop an overarching ecosystem-specific management strategy. This strategy must be based on what is realistic and desired to achieve when it comes to impacting expected and observed trajectories through ecosystem-based management. On the basis of these strategies, which specify potential and desired trajectories, it is possible in the next step to make specific goals and devise management interventions. This shift is in line with international trends in the fields of applied ecology. The strategy is based on dynamic concepts that aim to accommodate a suite of realistic and climate-adapted objectives and to a large extent maintain the fundamental structure, function and productivity of the ecosystem, despite significant changes in ecological condition. Through the formulation of phenomena, expectations and assessment of evidence for ecosystem change trajectories, the PAEC framework can be used as a vehicle for selecting realistic targets and interventions for ecosystem-based management and act as a tool for assessing the efficiency of such management. In this report we exemplify what are possible alternative management strategies for Arctic tundra ecosystems.

Sammendrag

System for vurdering av økologisk tilstand vil levere tilstandsvurderinger for alle terrestre og marine hovedøkosystemer som ikke er omfattet av EUs vanndirektiv. To vurderingsmetoder har blitt utviklet og anvendes nå for å gjennomføre de første fullskala vurderinger av skog, fjell, arktisk tundra og utvalgte marine økosystemer (Jakobsson et al. 2021, Jepsen et al. 2020). *System for vurdering av økologisk* tilstand er også tenkt å gi et faglig grunnlag for utarbeidelsen av forvaltningsplaner og formulering og vurdering av forvaltningsmål for norske økosystemer. Dette for å kunne innfri de ambisiøse målene for økosystem-basert forvaltning som er nedfelt i lovverket.

Tilstandsvurderingen av arktisk tundra er gjort av et bredt sammensatt vitenskapelig fagpanel som anvender vurderingsmetoden *Panel-basert vurdering av økosystemtilstand* (PAEC). Vurderingen, som er rapportert i sin helhet i Pedersen et al. (2021), oppsummeres i denne rapporten. Basert på et sett av 24 indikatorer for høyarktisk tundra og 42 indikatorer for lavarktisk tundra, konkluderer fagpanelet at: 1) Arktiske tundraøkosystemer i Norge har hatt betydelige endringer i de abiotiske forholdene, gjennom generelt økende temperaturer, varmere og lengere vekstsesong, kortere snøsesong og oppvarming og tining av permafrost, 2) De økologiske/biotiske konsekvensene av endringene for økosystemene er foreløpig begrensede, og tydeligst for økosystemegenskaper og indikatorer som har sterkest kopling til klima som påvirkningsfaktor, 3) Fundamentale økologiske strukturer og funksjoner er i hovedsak ivaretatt, slik at begge deløkosystemer fortsatt vurderes som å være i «god tilstand», 4) Visse biotiske komponenter av økosystemet, særlig i lav-Arktis, er på endringsbaner som bør betraktes som et varsel om at større endringer er under utvikling.

Både vurderinger av økologisk tilstand og økosystembasert forvaltning krever fokus på å skille effektene av forvaltningsbare og ikke-forvaltningsbare drivere fra naturlig variasjon. En robust vurderingsmetode må derfor etablere rutiner for å identifisere og kvantifisere årsakssammenhenger mellom drivere og tilstandsindikatorer. Dette er også en forutsetning for å vite hva en endring i en indikator faktisk indikerer. Den mest effektive måten for å avdekke slike sammenhenger, er å formulere driver–responssammenhenger som økologiske hypoteser. PAEC gjør dette i form av *fenomener*, som er kvalitative forventninger om retningsbestemte endringer i indikatorer, som konsekvens av relevante drivere. I noen tilfeller vil det være en entydig forventet relasjon mellom driver og indikator, slik at fenomenene har en høy gyldighet («validity»). I andre tilfeller kan flere drivere samvirke slik at det skaper komplekse responser i deler av eller i hele økosystemet. I PAEC uttrykkes slike kompliserte økologiske sammenhenger ved at fenomener har lav *gyldighet;* dvs. at den samlede effekten av driverpåvirkningene ikke er godt dokumentert og forstått. Gyldigheten av slike fenomener kan økes gjennom statistisk modellering av multi-driver–responser når et tilstrekkelig tilfang av overvåkningsdata er tilgjengelig. Vi viser til en rekke eksempler på hvordan denne type modellering, i regi av *Klimaøkologisk Observasjonssystem for Arktisk Tundra* (COAT), har bidratt til å øke gyldigheten av flere fenomener som inngår i PAEC for arktisk tundra.

Klimaendringene som nå overskygger alle andre drivere av tilstanden til arktiske økosystemer kan ikke forvaltes på økosystemnivå. Fordi disse økosystemene uansett vil være i rask endring — kanskje mot helt ukjente tilstander — vil det være utfordrende å sette oppnåelige forvaltningsmål. Vi anbefaler derfor at det utvikles overordnede, økosystem-spesifikke forvaltningsstrategier. Disse må baseres på vurderinger av hva som er realistisk mulig og ønskelig når det gjelder å påvirke forventede og observerte endringsbaner gjennom økosystembasert forvaltning. På grunnlag av slike strategier, som spesifiserer hva som er mulige og ønskede endringsbaner, kan det i neste steg bestemmes konkrete mål og forvaltningstiltak. Denne modus for økosystembasert forvaltning er i tråd med den internasjonale utviklingen av anvendt økologi. Den baserer seg på dynamiske

strategier for å nå realistiske, klimatilpassede mål for økosystemenes utvikling som til tross for store tilstandsendringer i størst mulig grad vedlikeholder viktige strukturer, funksjoner og produktivitet. Fordi PAEC, gjennom sin fenomentilnærming, fokuserer på forventede og observerte endringsbaner i økosystemets egenskaper, gir PAEC et godt grunnlag for å utvikle klimatilpassede strategier for denne typen økosystembasert forvaltning. I rapporten gir vi eksempler på hva som kan være aktuelle alternative forvaltningsstrategier for arktiske tundraøkosystemer.

Norsk arktisk tundra er delt inn i to delsystemer — lavarktisk tundra som ligger på det norske fastlandet og den høyarktiske tundraen som forekommer på Svalbard (foto). Foto: J. Stien/UiT

1 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 both founded on a unified, ecosystem-level definition of ”good ecological condition” that ”*ecosystem structure, function and productivity should not deviate significantly from [..] intact ecosystems*“ (Jakobsson et al. 2021, Jepsen et al. 2020). In broad terms this means that ecosystem condition should not be significantly impacted by modern industrial activities, including climate change (Nybø and Evju 2017).

The *System for Assessment of Ecological Condition* is suggested to form a basis for devising management plans and setting and evaluating management objectives for Norwegian terrestrial ecosystems. On an overall level, the management objectives for Norwegian ecosystems are ambitious, with an aim to be ecosystem-based. While the Norwegian legislation pertinent to Arctic ecosystems, governmental white papers (Box 1) and the *System for Assessment of Ecological Condition* all provide ultimate goals for the state of Norway's ecosystems, ecosystem-based management must be guided by objectives that are operational in the sense that they allow for effective management towards reaching realistic goals. In this context, the identification of causal driver–response relations are essential, both to quantify anthropogenic impacts and separate these from natural variability, and to evaluate the efficiency of management interventions on focal ecosystem components.

The PAEC assessment method is founded on ecosystem-based principles (Box 2) and accommodates the principal requirements for setting operational management goals. In this report (Box 3), we first summarise the principles of PAEC and the results and key conclusions from the first operational assessment of Arctic tundra (Figure 1; Pedersen et al. 2021) under the *System for Assessment of Ecological Condition* (Ch. 2). We then outline how PAEC is used to formulate causal links between ecological condition and drivers of change, in the form of *phenomena*, and provide a set of recent published examples where complex multi-driver relationships have been addressed for Arctic tundra ecosystem components (Ch. 3). Finally, we discuss what we believe are the principal requirements for setting operational management objectives, how PAEC accommodates these requirements, and lastly, how management under climate change may benefit from more from focus on managing ecosystem trajectories of change than ecosystem states (Ch. 4).

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[1] In Nybø and Evju (2017) termed «*Technical system for determining good ecological condition*».

Box 1. *Central, overall management objectives from Norwegian legislation and White papers relevant to ecosystem-based management of Low and High Arctic tundra ecosystems.*

Nature Biodiversity Act [1]

§ 4 (management objectives for nature types and ecosystems)

The objective
The objective is to maintain the diversity of nature types within their natural range and the species diversity and ecological processes that are characteristic of each habitat type. The objective is also to maintain ecosystem structure, functioning and productivity to the extent this is considered to be reasonable (Lovdata 2021).

§ 10 (ecosystem approach and total load)
An impact on an ecosystem shall be assessed on the basis of the total load to which the ecosystem is or will be exposed (Lovdata 2021).

White paper/Meld. St. 14 (2015–2016)
Nature for life — Norway's national biodiversity action plan [1])
The Norwegian action plan for natural diversity has as its main aim that ecosystems shall be in good condition, in order to protect biological diversity and to deliver ecosystem services. Well-functioning ecosystems give a basis for sustainable development (as interpreted by Nybø and Evju 2017).

The Svalbard Environmental Act § 1 [2]
The purpose of this Act is to preserve a virtually untouched environment in Svalbard with respect to continuous areas of wilderness, landscape, flora, fauna and cultural heritage. Within this framework, the Act allows for environmentally sound settlement, research and commercial activities.

White Paper/Meld. St. 32 (2015–2016)
Report to the Government — Svalbard
The overriding objective of the Svalbard policy is preservation of the area's distinctive natural wilderness. The White Paper stated this clearly in six overall objectives, where we list five of them which are particularly relevant to the management of tundra ecosystems.

- *On the basis of its internationally significant natural and cultural heritage, Svalbard shall be one of the world's best managed wilderness areas.*
- *Within the framework set by the Treaty and considerations of sovereignty, environmental considerations shall prevail in the event of conflicts between environmental protection and other interests.*
- *The extent of wilderness areas shall be maintained.*
- *Flora, fauna and cultural monuments that warrant protection should be preserved virtually intact, and natural ecological processes and biodiversity must be allowed to evolve virtually undisturbed by human activity in Svalbard.*
- *There shall be large and essentially pristine natural areas in Svalbard that meet the need for reference areas for climate and environmental research.*

1) Only mainland Norway
2) Only Svalbard

***Box 2**. Definition of ecosystem-based management (Christensen et al. 1996).*

A management driven by explicit goals, executed by policies, protocols, and practices, and made adaptable by monitoring and research based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem composition, structure, and function.

***Box 3**. Overview of specific objectives in the project assignment by the Norwegian Environment Agency.*

To conduct the first operational assessment of ecological condition of the Arctic tundra ecosystem, based on the Panel-based Assessment of Ecosystem Condition (PAEC) technical protocol version 2 (Jepsen et al. 2020).

→ In chapter 2 we give a summary of results and conclusions of the assessment of Arctic tundra according to the PAEC protocol. We supplement this by a short summary of the panel's working process in Appendix 2.

To identify and analyse influencing factors (drivers) that affect the ecological condition of the classified Arctic tundra ecosystem(s).

→ In chapter 3, we review basic principles and give examples of solutions for and how, based on PAEC, quantitative models can be used to analyse the total and partial loads of environmental impacts (drivers) on the ecological condition.

To describe how the PAEC assessment of Arctic tundra can contribute to a platform for setting ecosystem-based management objectives.

→ In chapter 4, we discuss how PAEC can form a basis for deciding on overall management strategies and setting specific objectives for ecosystems subjected to rapid climate change.

The management objectives for Norwegian Arctic tundra ecosystems are ambitious — with an aim to be ecosystem-based. Photos: N. Lecomte/NPI (left), R.A. Ims/UiT (right)

2 PAEC of Arctic tundra — summary and conclusions

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).

2.1 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 in Pedersen et al. (2021) for full definitions).

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

2.2 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 (Figure 1).

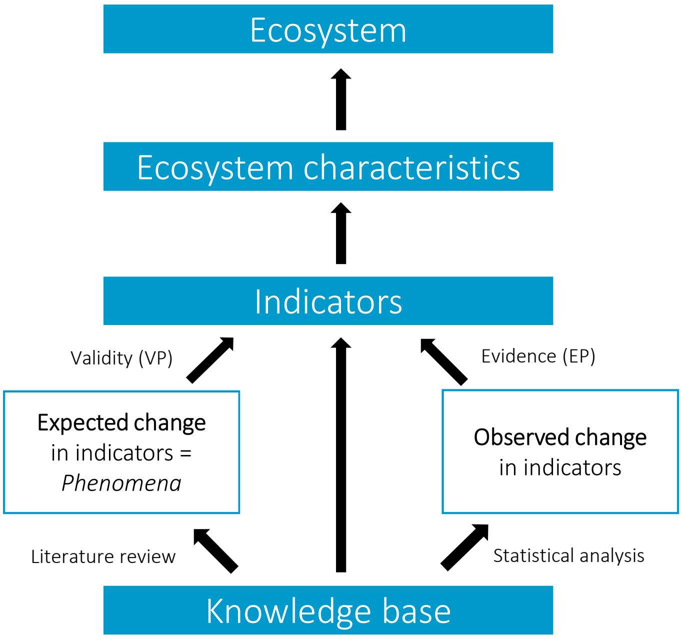


Figure 1. A schematic summary of the hierarchy in a PAEC assessment. The four main levels in PAEC (blue boxes) are assessments of; 1) the knowledge base, 2) the condition of individual indicators, 3) the condition of ecosystem characteristics and 4) the condition of the ecosystem as a whole. The assessment of the individual indicators rests upon the extent to which expected change 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 example in box). 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*). See Box 4 for an example.

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 21 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.

***Box 4**. 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 affects 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)

2.3 Datasets and indicators used in the assessment

The assessment of the condition of Arctic tundra ecosystems is based on analyses of 34 datasets 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 (Boxes 5 and 6). 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) 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 set of indicators contains e.g. 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: K.-O. Jacobsen©/NINA (upper left), F. Sletten/NPI (upper right), N. Lecomte/Université de Moncton, (lower left), T. Nordstad/NPI (lower right)

2.4 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*. The overall condition of each ecosystem characteristic is assessed as belonging to 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 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 to ***substantial deviation*** from the reference condition can no longer be considered representative of an intact ecosystem (Table 1).

Table 1. *Shortened definitions of the three assessment categories. For full definitions see 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 (Table 2).

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.

Table 2. *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 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 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.

Table 2 continued.

	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 bio-climatic 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 bio-climatic 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.

2.5 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 of abiotic conditions 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 (see Table 7.3.2a, b in Pedersen et al. 2021).

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 reduced 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.

2.6 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).

2.7 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 for 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 included 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 characteristic 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 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, while similar shifts in bioclimatic subzones are also occurring in the High Arctic. Photos: R.A. Ims/UiT (upper), C. Jaspers/NPI (lower)

Box 5. *Low Arctic tundra (bioclimatic subzone D and E) — indicators for each of the seven ecosystem characteristics. See Table 5.1a in Pedersen et al. (2021) for the associated phenomena.*

Photo: R.A. Ims/UiT

Ecosystem characteristic	Indicator
Primary productivity	Maximum vegetation productivity
	Start of growing season
	Plant biomass [1]
Biomass distribution among trophic levels	Plant growth forms versus rodents [1]
	Plant growth forms versus ungulates [1]
	Rodents versus carnivorous vertebrates
	Ungulates versus carnivorous vertebrates
Functional groups within trophic levels	Plant growth forms
	Herbivorous vertebrates
	Carnivorous vertebrates
Functionally important species and biophysical structures	Thicket-forming willows
	Crowberry biomass
	Mountain birch in forest-tundra
	Lemming abundance
	Ptarmigan density [3]
	Geometrid moth outbreaks [2]
	Semi-domestic reindeer abundance [1]
	Semi-domestic reindeer calf body mass [1]
	Semi-domestic reindeer calf rate [1]
	Red fox camera index
	Large predators [2]
Landscape-ecological patterns	Snowbed encroachment
	Bioclimatic subzones
	Wilderness areas
Biological diversity	Plant communities [2]
	Arctic fox abundance
	Arctic fox litter size
	Arctic fox camera index
	Snowy owl abundance
	Snowy owl fecundity
	Bird communities
Abiotic factors	Days with extreme cold
	Winter melt days
	Degree days
	Growing degree days
	Annual mean temperature [2]
	January mean temperature [2]
	July mean temperature [2]
	Annual precipitation
	Precipitation during growing season
	Snow cover duration
	Basal ice

[1] Development of existing indicator based on recommendations in the pilot assessment (Jepsen et al. 2019).

[2] New indicators developed in this assessment is based on recommendations in the pilot assessment (Jepsen et al. 2019, their Table 6.4).

[3] Dataset replaced/improved based on recommendations in the pilot assessment (Jepsen et al. 2019).

Box 6. *High Arctic tundra (bioclimatic subzone A, B and C) — indicators for each of the seven ecosystem characteristics.* See Table 5.1b in Pedersen et al. (2021) for the associated phenomena*.*

Photo: E. Eischeid/NPI

Ecosystem characteristic	**Indicator**
Primary productivity	Maximum vegetation productivity
	Start of growing season
Biomass between trophic levels	Maximum vegetation productivity versus Svalbard reindeer
	Maximum vegetation productivity versus geese
	Herbivorous vertebrates versus Arctic fox
Functional groups within trophic levels	Herbivorous vertebrates
Functionally important species and biophysical structures	Pink-footed goose abundance [1]
	Barnacle goose abundance
	Svalbard reindeer abundance [1]
	Svalbard reindeer mortality rate
	Svalbard reindeer calf rate
	Arctic fox abundance
Landscape-ecological patterns	Bioclimatic subzones
	Wilderness areas
Biological diversity	Svalbard rock ptarmigan breeding abundance
Abiotic factors	Days with extreme cold [3]
	Winter melt days [3]
	Degree days [2, 3]
	Growing degree days [2, 3]
	Annual mean temperature [2, 3]
	July mean temperature [3]
	Annual precipitation
	Permafrost
	Snow cover duration

[1] Development of existing indicator based on recommendations in the pilot assessment (Jepsen et al. 2019).

[2] New indicators developed in this assessment is based on recommendations in the pilot assessment (Jepsen et al. 2019, their Table 6.4).

[3] Dataset replaced/improved based on recommendations in the pilot assessment (Jepsen et al. 2019).

3 Identification and analysis of drivers of ecological condition

3.1 Levels of analysis of driver–response relationships

The identification of causal driver–response relations in ecosystems constitutes the core of ecological inquiries. It applies to: 1) basic research to unravel the fundamental principles that determine pattern (structure) and processes (functions) and 2) applied research to quantify impact of anthropogenic stressors and measure the efficacy of management interventions on components of biodiversity and ecosystem services. Drivers of changes in ecological condition can be identified and analysed on several levels, covering a continuum from simple qualitative formulation of *expected* driver–response relationships to formal statistical modelling with the goal of *estimating* the strength of often complex causal relationships, which exist between multiple drivers and the condition of one or more indicators. How confident the attribution to different driver–response relationships is varies greatly along this continuum, as does the potential information content for management. In Table 3 we have simplified this continuum into three levels. At the lowest level, driver–response relationships are determined based on current scientific knowledge, typically a literature review. This is relatively quick, can be summarised in simple tables and provides an overview of the drivers that are expected to be influential. However, the confidence of attribution will be highly variable and most often low, since driver–response relationships might be unaddressed in the literature, addressed in ecological contexts of low relevance for the specific ecosystem under assessment, and show high variability in relationships' strength (e.g. Clark and Hebblewhite 2021). Level 1 will rarely provide the opportunity of quantifying the relative importance of particular drivers or disentangling complex multi-driver relationships. As a basis for knowledge-based

Arctic fox abundance is influenced by multiple drivers such as reindeer carcass availability, marine subsidies and zoonoses in Svalbard. Multi-driver-response analysis of Arctic fox abundance is carried out in the COAT project. Photo: S. Cordon management decisions, level 1 is in most cases not sufficient. Both level 2 and level 3 aim to document causal driver–response relationships in contexts which are relevant for the ecosystem under assessment. In order to do this, some level of statistical modelling is required. At level 2, single-driver–response relationships are addressed. For indicators with a simple relationship to a single driver, which is of overriding importance relative to other drivers, a level 2 analysis might permit attribution with high confidence and also be sufficient to support active management decisions. However, most indicators of ecological condition are influenced by multiple drivers, which have main effect of different strengths and interact with each other. In most cases, analysis of single-driver–response relationships will not provide accurate attribution nor information content above an intermediate level of confidence. At level 3, multi-driver relationships are addressed with suitable, and more complex, statistical models compared to level 2. For indicators dependent on multiple, potentially interacting, drivers, this is the only way to disentangle the relative importance of individual drivers, and hence provide the understanding of causal driver–response relationships needed for knowledge-based management decisions.

Table 3*. An illustration of three levels at which driver–response relationships can be addressed along a continuum from simple formulations of expected relationships to formal analysis and attribution of causal relationships.*

Levels of analyses	**Information content for management**	**Confidence in attribution of driver–response relationships**
Level 1. Expected driver–response relations Approach: Literature review + identify important drivers for further analyses, experiments and monitoring	LOW	LOW
Level 2. Documented single-driver–response relations Approach: Simple statistical models + identify important drivers for further analyses, experiments and monitoring + quantify effects of single drivers + support management targeted at drivers with strong and stable relationships to ecological condition	MIDDLE	MIDDLE
Level 3. Documented multi-driver–response relations Approach: Complex statistical models + identify important drivers for further analyses, experiments and monitoring + quantify relative effects of multiple drivers + quantify interactions between drivers + support management targeted at drivers with simple or complex relationships to other drivers and to ecological condition	HIGH	HIGH

3.2 Attribution of driver–response relationships in a PAEC assessment

A PAEC assessment acknowledges the above-mentioned continuum in our ability to attribute driver–response relationships with confidence. The starting point for a PAEC assessment is therefore always a *level 1* assignment, where the expected main drivers of change in a given indicator are identified based on a literature review (see Chapter 5 in Jepsen et al. 2020). However, the available literature may contain relevant studies of *level 2* or *level 3* quality, which permits the links between these drivers and changes in the indicator to be identified with high certainty. PAEC therefore specifies that the understanding of the combined driver–response relationship should be further classified in two classes depending on whether this can be considered certain or less certain (e.g. whether they can be attributed with low or high confidence). Along with a similar classification, divided into two classes of our understanding of the role of a given indicator in the ecosystem, this forms the basis for scoring the *validity (VP)* of PAEC *phenomena*. PAEC phenomena (Ch. 5 in Pedersen et al. 2021) are simple qualitative hypotheses of the expected directional changes in ecological indicators under the pressure of mostly singular anthropogenic drivers, such as harvesting, land use or climate change. A phenomenon of high validity is one where the links to the identified set of anthropogenic drivers are considered relatively certain, and the understanding of the role of the indicator in the ecosystem is considered good. In other words, it represents a scientifically well-founded hypothesis of how anthropogenic drivers are expected to change the condition of an indicator, and the implications such changes may have for the ecosystem being assessed.

However, it is important to keep in mind that even though we might be able to identify the most important drivers behind changes in a given indicator with a fair amount of certainty based on available literature, this does not necessarily mean that the relative importance of drivers, and the extent to which several drivers interact, are known. This means that even phenomena of high validity (VP) are rarely supported by studies of *level 3* quality (Table 4). Furthermore, many of the phenomena score low in terms of validity. There are several reasons for this. Some indicators are proxies (surrogates) that have poorly validated relations to the ecological characteristics that they are supposed to represent (Lindenmayer and Likens 2011). Hence, phenomena and change rate estimates that are derived from analyses of proper state variables, rather than surrogate indicators, yield inferences that are more robust. However, the most common cause of low validity for phenomena, even when proper state variables are concerned, is that most ecological response variables are simultaneously subjected to multiple drivers of change. In that case, formulation of alternative phenomena, sometimes with opposite expected directional changes and ecological impacts, can be justified. Consequently, the outcome of total loads in a multi-driver context cannot be derived in verbal terms (i.e. on *level 1* in Table 3) or even with simple single driver models (*level 2* in Table 3). Instead, formal analysis of ecological responses, as functions of multi-driver impacts, must be done with quantitative models that are formulated in mathematical terms (i.e. *level 3* in Table 3).

There is a large scientific literature on how to build and analyse quantitative ecological models to make causal inferences about complex driver–response relations in ecosystems subjected to environmental change (for recent reviews see Laubach et al. 2021, Williams et al. 2021). For the two Arctic sub-ecosystems targeted by the present PAEC assessment, a modelling framework for analysing ecosystem state variables derived from COAT is outlined in Ims et al. (2013b). In this framework, the first step is to construct graphical models that specify impact paths between state variables measuring drivers (i.e. climate, or management interventions such as harvesting, land use, conservation actions) and state variables measuring biotic responses (see Ims et al.

2013b). In fact, most of the phenomena in the Arctic tundra PAEC assessment are derived from COAT's graphic ”impact-path models”, which each encompasses several linked phenomena. The next step is to build and analyse statistical models. These are often described as structural equation models or hierarchical state-space models that estimate the coefficient of the impact paths (i.e. the effects size of drivers on the state variable) by accounting for biotic interactions that potentially confound, interact with, or mediate the driver effects. Such models rely heavily on the spatio-temporally extensive, ecosystem-based monitoring time-series that only recently have started to become available from COAT and MOSJ. See Boxes 5 and 6 for a complete overview of the indicators derived from these programmes and applied in PAEC of Arctic tundra and Appendix 4 for indicators which have one or more manageable, anthropogenic drivers (e.g. hunting, land use, natural resource management), relevant for driver–response analysis that can improve our ability to attribute change in the indicators to specific drivers.

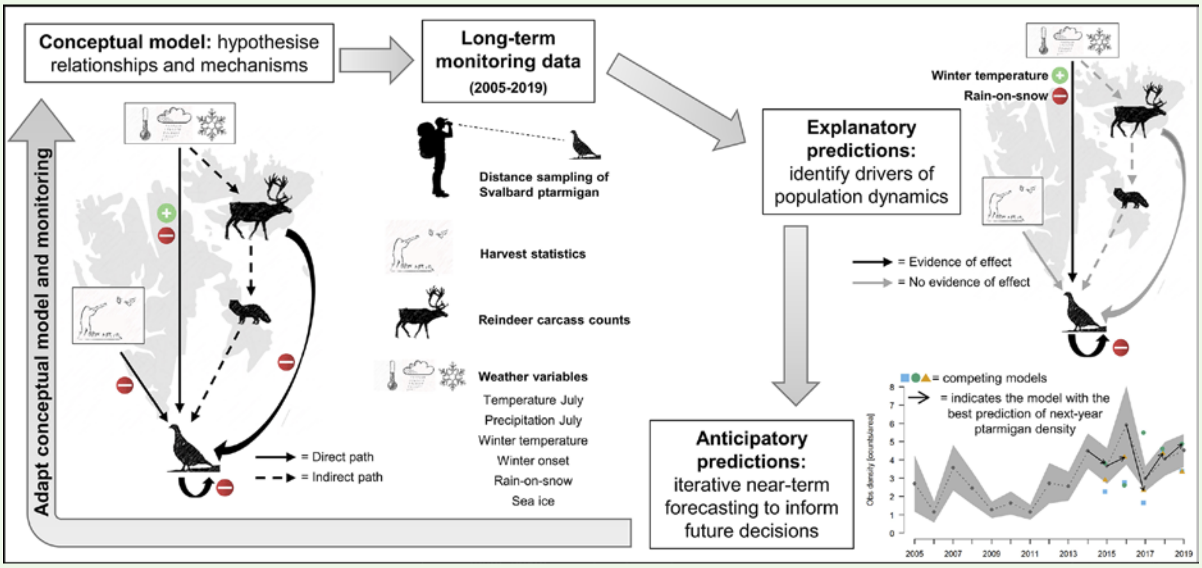
In conjunction with the development of the PAEC protocol, COAT members and the related research project SUSTAIN (*Sustainable management of renewable resources in a changing environment: an integrated approach across ecosystems*), have analysed a set of statistical ecosystem models that explicitly address ecological indicators (i.e. state variables) that are subjected to multiple change drivers, and hence have had associated phenomena with relatively low scores for VP. A sample of such related models that have been quality assured in terms of passing peer review of scientific journals is listed in Table 1.

Such *level 3* models are not an integrated part of a PAEC assessment, but serve to improve the foundation for a PAEC assessment in several ways:

- **Quantifying the relative importance of drivers**: The effects of drivers, both additive and their interactions, are statistically tested and quantified so that the validity of the phenomena is strengthened. In some cases, the modelling has led to reformulations of phenomena, in the sense that the expected direction of change in an indicator has changed sign from negative to positive (e.g. the impact of climate change on the Svalbard ptarmigan; Marolla et al. 2021, see Box 7).
- **Separating effects of manageable and non-manageable drivers**: Several of the models separate the effect of climate change from other anthropogenic drivers, such as harvesting, so that it can be assessed to what extent manageable drivers contribute significantly to the total loads on certain species or ecosystem characteristics (Henden et al. 2020, Nater et al. 2021).
- **Strengthen the understanding of the role of indicators in the ecosystem**: The models formulate and thereby assess the linkages between different phenomena and ecosystem characteristics. Hence, the models provide means to assess the wider significance of one driver–response relations on another, for example the effect of climate-induced increased primary productivity on predator–prey relations that ultimately affects components of Low Arctic biodiversity (Ims et al. 2019).
- **Provide an adaptive framework for continuous updates**: The models are intended to be regularly updated as the data series from the observation system (e.g. COAT and/or MOSJ) become longer, more spatially extensive or more complete (additional state variables). In context of the present PAEC assessment of Arctic tundra, the model of Henden et al. (2020) was updated with data from four more years that strengthened the inferences about driver impacts and hence the validity of the phenomenon related to the willow ptarmigan indicator for the ecosystem characteristic *Functionally important species and biophysical structures* in Low Arctic tundra.

- **Provide short term forecasts**: The models can be used to provide forecasts both on short (Henden et al. 2020, Marolla et al. 2021) and longer (Hansen et al. 2019a) time horizons. Such forecasts are important for assessing models and providing tools for decisions regarding manageable drivers. See Box 7 for an example.

Box 7. *Iterative model predictions for wildlife populations impacted by rapid climate change.*



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

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

This study highlights the value of the ecosystem-wide COAT-based monitoring in Svalbard and the application of multi-driver statistical modelling based on these monitoring data to assess and forecast the state of Svalbard rock ptarmigan populations. In context for PAEC, the model of Marolla et al. (2021) substantially improves the validity of the phenomenon (VP) for the High Arctic ptarmigan indicator.

There are several further advances from the current suit of developed COAT/SUSTAIN models that benefit the PAEC assessment of Arctic tundra and improve its ability to function as a knowledge platform for setting management objectives (see Ch. 4 and Mellard et al. 2021). Particularly, there is scope for building more comprehensive ecosystem models that simultaneously assess several ecosystem characteristics (Williams et al. 2020). Such an advancement will allow for better assessment, not only of the total loads of multiple stressors, but also for estimation and forecast of possible trade-offs between ecosystem characteristics, their total impacts and ecosystem-level significance. More than anything, such holistic models require more comprehensive, long-term ecosystem-based monitoring than is presently in place in the Norwegian Arctic.

The endemic sub-species Svalbard rock ptarmigan is an indicator of High Arctic biodiversity in Svalbard. During recent years the ptarmigan populations have shown an increasing trend, which multi-driver statistical modelling (see Box 7) has shown can be attributed to higher winter temperatures. Photo: N. Lecomte/NPI

Table 4. *Peer reviewed models analysed to quantify multi-driver effects on components (state variables and ecosystem characteristics of Norwegian Low and High Arctic tundra) and how they encompass different phenomena of the current PAEC assessment of Arctic tundra (Pedersen et al. 2021). Phenomena and biotic state variables in bold represent the response targeted in the model, while the other phenomena and state variables act as ecosystem (biotic and abiotic) drivers. Management state variables in bold represent management interventions (i.e. management drivers) that are explicitly quantified in the model. The others (not in bold) can be assessed indirectly, since they determine one or more of the biotic drivers. See Appendix 3 and Table 5.1a, b in Pedersen et al. (2021) for listing of indicators and associated phenomena. LP = Low Arctic phenomenon, HP = High Arctic, NA = not included in the model.*

			State variables			
Ecosystem characteristic	**Phenomena**	**Model type**	**Biotic**	**Abiotic**	**Management drivers**	**Reference**
Low Arctic *Functionally important species and biophysical structures, Primary productivity*	LP16, LP02, LP14, LP17, LP33, LP40	State-space (hierarchical distance sampling) structural equation model	Willow ptarmigan population growth, density-dependence, rodent abundance, reindeer carrion, geometrid moth outbreaks	Summer temperature, summer precipitation, onset of winter (snow cover)	Ptarmigan harvest, reindeer management	Henden et al. (2020)
Low Arctic *Functionally important species and biophysical structures, Biological diversity*	LP16, LP06, LP14, LP19	Generalised linear mixed model according to BACI design for the management intervention	Willow ptarmigan population density, rodent abundance, reindeer carrion	NA	Meso-predator control, ptarmigan harvest	Henden et al. (2021a)
Low Arctic *Functionally important species and biophysical structures, Primary productivity*	LP21, LP18, LP20, LP23	State-space structural equation model	Reindeer calf production and body weight, density-dependence, onset of plant growth (spring), maximum primary productivity, number of large carnivore family groups	Snow depth	Carnivore management, reindeer management	Henden et al. (2021b)
Low Arctic *Biological diversity, Primary productivity*	LP33, LP01, LP25, LP27	Generalised linear mixed model according to experimental design	Tundra bird nest predation, maximum primary productivity (greenness), small rodent cycle phase, vegetation cover	Elevation (proxy for annual mean temperature)	NA	Ims et al. (2019)
High Arctic *Biological diversity, Functionally important species and biophysical structures*	HP15, HP10, HP12, HP16, HP17, HP25	State-space (hierarchical distance sampling) structural equation model	Svalbard rock ptarmigan population growth, density-dependence, reindeer carrion	Summer and winter temperatures, summer precipitation, rain-on-snow, sea ice extent, onset of winter (snow cover)	Ptarmigan harvest	Marolla et al. (2021)
High Arctic *Functionally important species and biophysical structures*	HP12, HP10, HP16	Integrated population model (IPM) combined with Life Table Response Experiments (LTRE)	Arctic fox breeding population size and demography, density-dependence, reindeer carrion, goose populations	Winter temperature, sea ice extent	Arctic fox harvest	Nater et al. (2021)
High Arctic *Functionally important species and biophysical structures*	HP08, HP15, HP18, HP21	Age-structured population model combined with LTRE and structured equation model of reproductive stages	Barnacle goose population size and demography, density-dependence, Arctic fox abundance	Temperature, onset of plant growth, precipitation	NA	Layton-Matthews et al. (2020)
High Arctic *Functionally important species and biophysical structures*	HP09, HP10, HP12, HP21	Integrated population model (IPM) combined with stochastic simulations Generalised linear mixed model	Svalbard reindeer population size and demography, density-dependence	Summer temperature, winter length, rain-on-snow	NA	Hansen et al. (2019b), Hansen et al. (2019a)

4 PAEC as a knowledge platform for setting management objectives

4.1 Principle considerations and requirements

The *System for Assessment of Ecological Condition* [2] 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). While two alternative assessment methods have been developed (PAEC and Index-based Ecological Condition Assessment [IBECA]); Jakobsson et al. 2021), there is an agreed unified, ecosystem-level definition of "good ecological condition" that *"ecosystem structure, function and productivity should not deviate significantly from [..] intact ecosystems*" — in broad terms meaning an ecosystem condition that is not significantly impacted by modern industrial activities, including climate change (Nybø and Evju 2017). This definition is formulated in a manner so that it may be applied as a general ecosystem-level management objective, principally, on the same terms as the ecosystem management objectives of Norwegian legislation (Nature Diversity Act (§ 4) and the Svalbard Environmental Protection Act § 1; see Box 1). Following the general overall management objectives, the chapter by Ims et al. (2017) in Nybø and Evju (2017) formulated definitions and criteria for Norwegian High Arctic and Low Arctic tundra that in principle can be applied as ecosystem-level management objectives for these regions (Box 8). Further, Ims et al. (2017) provided definitions/objectives for each of the seven ecosystem characteristics (see Nybø and Evju 2017, pages 83-85 and 88-90).

Box 8. *Management objectives for Norwegian Arctic tundra ecosystems according to the definition of "good ecological condition" given in Nybø and Evju (2017).*

High Arctic tundra (Svalbard)	Low Arctic tundra (Finnmark)
The structure and functioning of the ecosystem in Svalbard shall be set by a High Arctic climate. Primary production is higher than decomposition (mineralisation) of organic materials so that the ecosystem stores carbon, of which most is maintained in permafrost. The food web is composed of functional groups, and regulated by trophic interactions and marine subsidies, that are typical to Svalbard. Species communities shall include viable populations of typical High Arctic species as well as sub-species that are endemic to Svalbard. The communities shall not be subjected to increasing abundance or colonisation of Low Arctic, or boreal species as a result of climate change or invasive (introduced) species resulting from anthropogenic activities. Snow cover shall have a depth, quality and seasonality that provide life conditions for High Arctic species and communities and affect energy fluxes between the ecosystem and the atmosphere in a manner that does not contribute to climate warming.	The structure and functioning of ecosystem shall be set by a Low Arctic climate. Primary production is higher than decomposition (mineralisation) of organic materials so that the ecosystem stores carbon. The food web is composed by functional groups, and regulated by trophic interactions, that are typical to Low Arctic tundra and the adjoining forest-tundra ecotone. Species communities shall include viable populations of typical Low Arctic species and not be subjected to increasing abundance or colonisation of species from boreal and temperate ecosystems resulting from climate change or human facilitated species range expansions resulting from anthropogenic activities. Snow cover shall have a depth, quality and seasonality that provide life conditions for Low Arctic species and communities. Snow cover and vegetation communities affect energy fluxes between the ecosystem and the atmosphere in a manner that does not contribute to climate warming.

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[2] In Nybø and Evju (2017) termed «*Technical system for determining good ecological condition*».

Ecosystem-based management is destined to be the mode for sustainable use and conservation of nature in Norway. While both the Norwegian legislation (Box 1) and the *System for Assessment of Ecological Condition* provide ultimate goals for the state of Norway's ecosystems, ecosystem-based management must be guided by objectives that are operational in the sense that they allow for effective management options towards reaching realistic goals. To devise operational ecosystem-based management objectives there are two fundamental requirements that must be met:

1) Establishing causal links between drivers of change and ecosystem condition

Ecosystems are subjected to multiple drivers of change. Operational ecosystem management must be grounded on science-based knowledge about the impact of each driver and their cumulative impact on ecosystem function, structure and productivity. The Norwegian Nature Diversity Act (§10) states that according to an ecosystem approach "*an impact on an ecosystem shall be assessed on the basis of the total load to which the ecosystem is or will be exposed*". This implies that when multiple drivers cause impacts on an ecosystem or its imbedded characteristics, the assessment method should be able to identify the impacts of each driver as well as their potential interactions. For instance, several of the indicators of Arctic ecosystem characteristics are simultaneously impacted by both climate change and resource use. The total load of the two drivers depends on their separate strengths and signs, whether they act in an additive manner or whether they interact in a synergistic or antagonistic manner. The specific nature of the interaction will have bearing on how resource use should be best managed under climate change.

2) Identifying operational drivers for effective ecosystem-based management interventions

Among the multiple drivers of changing ecosystems, there will be drivers of different types. There may be drivers in which causal links to ecosystem state/change are scientifically certain, strong and pervasive, while effects of other drivers may be scientifically uncertain, weak and with limited impact. The key to operative management is to focus on the former type since it helps to identify "corridors of clarity" for effective decisions and actions (cf. Polasky et al. 2020). Another important distinction is between drivers that are readily manageable at the scale of or within the target ecosystem, and those that are not. Land use and harvesting are examples of the former, while climate change and long-distance transported pollutants are examples of the latter. Ecosystem-based management should normally focus on the drivers that are manageable at the ecosystem scale, while the requirement of accounting for the total load (cf. point 1) also demands that drivers beyond the ecosystem scale must be considered.

4.2 PAEC and requirements for setting operational management objectives

How does PAEC accommodate the two principal requirements regarding operational objectives for ecosystem-based management?

Regarding establishing causal links (point 1 above), the phenomena formulated by PAEC are central. The phenomena specify causal links between anthropogenic drivers of change and indicators of ecosystem function, structure and productivity. The causal links are verbally expressed in terms of qualitative predictions on directions of change trajectories for ecological indicators and their ecosystem significance (see Pedersen et al. 2021). 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 change trajectories (i.e. estimated rates of change that are beyond deviations due to natural variability) are consistent with the prediction (EP — *Evidence for phenomena*). In case of unambiguous expectations (there are no known alternatives) for simple causal driver–response relations, the estimated trajectory of an indicator will suffice for PAEC to verify a phenomenon. However, to formally assess phenomena of uncertain prior validity and, particularly under rapidly changing ecosystem characteristics subjected to multiple drivers and potentially diversified responses, model-based analyses of driver response relations (Ch. 3, Appendix 4) should be coordinated with PAEC. This is because such quantitative modelling is the only way to assess total load and to quantify the impacts of separate and potentially interactive drivers and their wider ecosystem significance. Such modelling is also required for assessment of specific management interventions. For Arctic tundra ecosystems, the PAEC assessment has been developed in tight conjunction with such model developments in the project SUSTAIN (SUSTAIN 2021) and COAT (COAT 2020). A well-known situation is the lack of desired data coverage or insufficient monitoring data series, but the method is designed for handling this situation.

Regarding identifying operational drivers for effective ecosystem-based management (point 2), the overwhelmingly most important driver in the phenomena assessed for tundra ecosystems is climate change. Indeed, the main conclusion of the present PAEC assessment for Norwegian Arctic tundra (Ch. 2 and Pedersen et al. 2021), as well as previous international assessment of terrestrial Arctic ecosystems (e.g. ACIA 2004, Ims et al. 2013a), is that climate forcing currently overshadows all other pressures on these ecosystems. As noted above, climate change belongs to the type of drivers that cannot be managed at the scale of the ecosystems, but nevertheless needs to be accounted for when assessing total loads and those drivers that are manageable, such as land use and harvesting (as exemplified in Table 4). It is important to know if such manageable drivers simply add to the total load or interact synergistically or antagonistically with climate change.

Several of the PAEC phenomena for Arctic tundra are formulated as functions of multi-driver loads that include drivers that are manageable at the ecosystem level in addition to climate forcing. For instance, semi-domestic reindeer management in Low Arctic tundra may further enhance abundance of boreal generalist predators that benefit from a climate-induced increased primary productivity (e.g. increased food availability contributing to larger reindeer populations, and subsequently more prey and carcass availability), while at the same time reindeer management may have an antagonistic effect on climate-induced expansion of tall shrubs and trees (i.e. reindeer grazing maintains open tundra; Bråthen et al. 2017, Christie et al. 2015). Hence, management may directly use the phenomena of PAEC, considering their validity and evidence, to identify specific management objectives and devise interventions — pending on a decision of an overall ecosystem-level climate strategy (see below). However, we recommend that the qualitative PAEC phenomena for the indicators should be translated into quantitative models of state variables, as to provide quantitative assessment of the effects of the interventions (as exemplified in Ch. 3). Such models can even be used to solve trade-off situations in terms of specifying formal "objective functions" (Runge and Walshe 2014). For instance, given a decision for an overall management strategy (see below) that aims to resist the transition of open tundra to shrub-lands, models can be used to predict the abundance of browsing herbivores (e.g. moose and/or reindeer; Bråthen et al. 2017) that is required for this purpose, while avoiding at the same time herbivore carrions that facilitate increasing populations of boreal meso-predators (Henden et al. 2014). Note that such models need to incorporate interactions with weather and climate change, as both the increase of shrubs and the mortality of herbivores are highly dependent on climate.

Semi-domestic reindeer management in Low Arctic tundra may enhance abundance of boreal generalist predators that benefit from a climate-induced increased primary productivity (e.g. increased food availability contributing to larger reindeer populations, and subsequently more prey and carcass availability), while at the same time reindeer management may have an antagonistic effect on climate-induced expansion of tall shrubs and trees (i.e. reindeer grazing maintains open tundra). Photo: L.E. Støvern/UiT (upper left), G. Vie/UiT (lower left), G. Vie/UiT (right)

4.3 Management strategies for ecosystems under climate change

Current national policies that shape carbon dioxide emissions put the world on track for a 2.3–4.1°C rise in the global temperature by 2100 (Turney et al. 2020). Due to the polar amplification of climate change, the Arctic and northern boreal regions may experience an increase in temperature up to three times the global average (Davy and Outten 2020). Such an extreme warming rate implies massive changes to cold-adapted ecosystems that must be taken explicitly into consideration in ecosystem-based management now and for all foreseeable future. With such climate change prospects, it is impossible to provide long-term predictions of ecosystem conditions because novel, likely transient and non-equilibrium, ecosystems with unknown properties will emerge (Hobbs et al. 2017). Consequently, it is also difficult to set concrete management objectives that can be attained with a high likelihood. Accordingly, Barnosky et al. (2017) suggested that rather than attempting to hold ecosystems to an idealised conception of the past, as has been the prevailing management paradigm, maintaining vibrant ecosystems for the future requires new approaches that aim to manage ecosystems for functional integrity rather than trying to attain unrealistic past states. Indeed, for Arctic ecosystems — soon situated way outside the bioclimatic envelopes that are necessary to keep them intact — devising management objectives in terms of conditions that characterise a past reference climate (cf. Box 8) is utopian. Thus, management goals must be based on decisions on what could be realistic and rational *climate strategies* that take explicitly into account the ecosystem impacts of climate change. Internationally, the fields of applied ecology have moved away from static objectives and concepts rooted in historic baseline reference conditions towards more dynamic concepts of ecosystem renovation to accommodate a suite of overarching and flexible climate-adapted objectives (Prober et al. 2019).

Accordingly, the most rational management strategy for ecosystems strongly forced by climate change, is to explicitly plan for managing *rates* (trajectories) rather than attempting to attain or restore past *states* (Williams et al. 2021). Focusing on trajectories:

- escapes the problem of precisely defining “correct” reference states (baselines) and thresholds when knowledge about such states/thresholds is non-available or poor
- is more analytically feasible, as estimating rate of change, based on time-series monitoring data, is more robust than attempting to define thresholds that may be arbitrary or states that are likely non-steady (transient)
- conforms to the analytical framework of the PAEC protocol (Jepsen et al. 2020) that estimates change rates in indicators of ecosystem structure, function and productivity
- offers opportunities to assess the significance of change rates along a continuum from abrupt to slow, as suggested by Williams et al. (2021), and according to their position on the VP (validity of phenomenon) and EP (evidence for phenomenon) axes of PAEC
- facilitates adaptive and open-ended management strategies when the outcomes and endpoints of ecosystem change are unknown, because of the large uncertainty of the realised extents and impacts of future climate change and other anthropogenic stressors
- offers opportunities for modifying climate-driven change trajectories (i.e. slowing down or altering direction) that also are subjected to manageable drivers of change at the ecosystem-level (e.g. land-use and harvest).

Although managing trajectories of ecosystem change appears to be the best way forward, there are still some overarching challenges that must be met. First and foremost, monitoring data must be available to estimate and assess such trajectories. Next, decisions on ecosystem-level *management strategies* are needed before specific *management objectives* can be set at the level of ecosystem characteristics and indicators. For example, the region currently harbouring a Low Arctic ecosystem in Finnmark may be on a trajectory towards a warm-temperate climate before 2100. In an equilibrium state, the warm-temperate climate zone is expected to harbour a boreonemoral forest ecosystem. However, due to the slow rate of forest colonisation (Talluto et al. 2017), Finnmark will likely not have boreonemoral forest in 80 years. The PAEC assessment of tundra indicates that the present ecosystem in East Finnmark is already in a (dis-equilibrium) transient state with a mixture of slow (time-lagged), fast and abrupt trajectories in different characteristics of the ecosystem (see illustration below for an example). The prospects for the future climate indicate that such complex ecosystem change trajectories will be enhanced in the coming decades. While some of the climate-induced changes are beyond management interventions (e.g. geometrid moth outbreaks), other may be within the realm of management interventions (e.g. shrub and forest encroachment). We also note that strong and fast climate forcing without certain endpoints and the potential for the emergence of novel, non-analogous climates represent a fundamental challenge to devising long-term strategies.

The fundamental question is then, within the realm of possible management interventions in case of ecosystems strongly impacted by climate change — what should be the overall management strategy?

Such overall management strategies should account for ongoing and likely emergent transitions at the ecosystem-level. On that basis, alternative options for ecosystem-level management strategies may be envisioned. The current ecosystem management objectives of Norwegian legislation (Nature Diversity Act (§ 4) and the Svalbard Environmental Protection Act § 1; see Box 1) appear to implicate a strategy that should resist any transition away from intact ecosystem states (cf. Box 8) that could *inter alia* cause loss of endemic biodiversity. In the case of Low Arctic tundra ecosystems, there will certainly be loss of Arctic species that require open tundra habitats when shrub-land or forest encroach on the tundra. In such a case there may be an option to direct the ecosystem-level change trajectory towards "open lowlands" (Nybø and Evju 2017), to preserve a habitat structure that possibly may harbour some tundra species. Such semi-natural ecosystems (heathlands or grasslands) are presently maintained by e.g. heavy management regimes in terms of high grazing/browsing pressure from domestic herbivores and burning on the south-west coast of Norway. Indeed, under the current management regime of semi-domestic reindeer in Finnmark, recent research (Bråthen et al. 2017) and the present PAEC support that the browsing pressure currently prevents tall shrubs to encroach on open tundra. Also, the recent spreading outbreak of geometrid moths into the forest-tundra ecotone and Low Arctic shrub-lands enhances the feasibility of resisting this sort of ecosystem transition. The complete opposition to such a *transition-resistance strategy* could be to assist a fast transition of Low Arctic tundra and the sub-Arctic forest-tundra ecotone to a proper forest ecosystem by planting and naturalising stands of boreonemoral tree species (Bellemare and Deeg 2015). The rationale for such a *transition-facilitating strategy* could be to maximise the ecosystem's capacity for carbon sequestration and/or to provide habitats for boreonemoral biodiversity that may be threatened by climate change further south. The choice between alternative ecosystem management strategies, which both may be scientifically plausible, needs to be based on careful consideration of major trade-offs between different ecosystem functions (including ecosystem services) and biodiversity (e.g. species of conservation concern), as well as the feasibility of balancing such trade-offs under the practical and economic constraints that may be associated with the alternative strategies. Decision on overall strategies in terms of scientifically validated, manageable corridors for future ecosystem trajectories (Jackson and Hobbs 2009, Polasky et al. 2020) must be made before specifying more detailed management objectives of separate ecosystem characteristics and species. Unavoidably, which strategy to choose will involve value-laden (political) considerations that are beyond the domain of scientific inquiries, as will be the case when trade-offs between different ecosystem services and/or biodiversity is involved. Such value-laden political decisions have already major bearing on how Norway's ecosystems are managed. Examples are how large carnivores and most of the nation's forests are presently managed. In both cases, an overall strategy/decision with respect to which ecosystem service is considered most favourable (production of livestock and wood) is needed before specific objectives are set for other ecosystem functions and structures that will be impacted by this strategy. Similarly, specific climate strategies for Norway's ecosystems should be set before detailed objectives are specified under these strategies.

Marine ecosystems in Norwegian waters are changing due to climate change in similar ways as in Arctic tundra ecosystem — possibly at even faster rates (Arneberg et al. 2018, Arneberg et al. 2020, Jepsen et al. 2019). For example, the North Sea is currently on a trajectory of change that may generate a new ecosystem where northern zooplankton species, which are largely spring-spawning, are replaced by more southerly and summer-spawning zooplankton. This sets off a shift in the fish communities, with the spring-spawning fish stocks that have traditionally dominated the system (such as cod, haddock and herring), being replaced by more southerly fish species that are

The assessment of Low Arctic tundra indicates that the present ecosystem in East Finnmark is already in a (dis-equilibrium) transient phase with a mixture of slow (time-lagged), fast and abrupt trajectories in different components of the ecosystem. Here illustrated by geometrid moth outbreak (fast change) causing massive die-off of mountain birch forest (fast change) with slow forest recovery (slow change). Management interventions, in the form of salvage logging of dead or heavily damaged birch stems, help to speed up the forest recovery process. Photos: J. Iglhaut/NINA (top), O.P. Vindstad/UiT (left)

able to utilise summer-spawning zooplankton to reproduce (e.g. European bass, anchovies and sardine; Arneberg et al. (2018). Although the options for management are very different in marine and terrestrial systems, the lack of relevance of past states as goals for management and the need to develop management strategies for the ecosystem changes that will occur in the future, clearly applies also for the terrestrial realm. For example, if existing fish stocks are to be replaced by new ones, management strategies for this can be developed. This can result in fisheries management explicitly aimed at building up these new stocks to ensure that large fish stocks are indeed a functionally important part of the ecosystems.

5 Recommendations for the management of Arctic tundra

Based on the considerations presented in chapters 3 and 4 of this report and our experiences from the first operational *Panel-based Assessment of Ecosystem Condition* of Arctic tundra (Pedersen et al. 2021), we arrive at the six following recommendations:

- Considering the prospects of fast and extensive climate change in Norway's boreal, alpine and Arctic ecosystems, we recommend that overall ecosystem-specific *climate strategies* should be a priority. Such strategies should be based on expected and observed trajectories of ecosystem change rather than on a concept of specific ecosystem states and thresholds. Definitions of climatic reference periods, i.e. ecosystems in "good condition" (Box 8), are useful as baselines for assessing deviations, but not for setting management objectives. Regardless of the chosen management strategy, we expect fundamental ecosystem changes during the next decades that will push Norway's Arctic ecosystems far away from their reference conditions.
- Decisions based on consideration of alternative management strategies, which eventually may involve interventions to modifying ecosystem-level trajectories, should be made before setting specific management objectives for separate ecosystem characteristics or indicators. Alternative strategies could range from attempts to resist climate-induced changes in order to preserve endemic Arctic biodiversity, to the promotion of fast ecosystem transitions in favour of functions that may mitigate against positive ecosystem feedbacks to global warming. The choice between such strategies involves difficult, value-laden considerations that are beyond the realm of natural sciences.
- PAEC can aid in the development of overall management strategies and subsequent specific objectives. This is because change trajectories and their causal relations to climate change and manageable ecological change-drivers represent the core of PAEC. Hence, PAEC can identify options that may be within the reach of realistic ecosystem stewardship (Chapin et al. 2010).
- Analyses of quantitative multi-driver models, based on PAEC phenomena, are needed to identify concrete management options. This will eventually help devising design for and assess efficacy of interventions that intend to alter ecosystem change trajectories that are deemed undesirable under a chosen management strategy. Some PAEC-related models (i.e. change rate models) have already been used for such purposes (Table 1).
- A tight, continuous interaction between ecosystem scientists, managers and policy makers is needed to tackle the challenge of achieving sustainable management of Norway's ecosystems subjected to climate change and other stressors. PAEC can offer a knowledge platform for such an interaction, where both the complexity of the ecosystems and the need for concrete management objectives and actions are incorporated and merged.
- An ecosystem-based management for the future will require further development of the long time-series through ecosystem-based adaptive monitoring programmes (Ims and Yoccoz 2017). Without data on actual rates of change and deviations from the defined reference states, management actions cannot be science-based. Predictable funding for ecosystem-based adaptive monitoring programmes is a prerequisite for the continuation of the time series and other data sources upon which the assessment of ecological condition in Arctic tundra currently rests.

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7 Appendices

Appendix 1: List of panel members

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Appendix 3: List of phenomena in Table 2

Appendix 4: List of indicators that are applied in PAEC of Arctic tundra, which have one or more manageable, anthropogenic drivers

Indicators with one or more manageable, anthropogenic drivers (e.g. hunting, land use, natural resource management) are most relevant for in depth supplementary driver–response analysis to improve our ability to attribute change in the indicators to specific drivers. Here illustrated by three indicators from High Arctic tundra (Pink-footed-goose, Svalbard reindeer and Svalbard rock ptarmigan) and three indicators from Low Arctic tundra (semi-domesticated reindeer, red fox and shrublands). Photos: T. Nordstad/NPI (upper left), N. Lecomte/NPI (lower left), R. Ims/UiT (upper right). G. Vie/UiT (middle right), E. Soininen/UiT (lower right)

Appendix 1: List of panel members

Table A1. *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. NPI = Norwegian Polar Institute, UiT = The Arctic University of Norway, MET Norway = Norwegian Meteorological Institute, NINA = Norwegian Institute of Nature Research, 5) AU = Aarhus University.*

Name, institution, email	Role	Expertise
Åshild Ø. Pedersen, NPI (aashild.pedersen@npolar.no)	Project manager, leader of scientific panel, expert	Svalbard reindeer, Svalbard rock ptarmigan, food web ecology (HA)
Hanna Böhner, UiT (Hanna.bohner@uit.no)	Expert	Plant biomass, plant growth forms, food web ecology (LA)
Kari Anne Bråthen, UiT (kari.brathen@uit.no)	Expert, participant in scientific panel	Plant biomass, plant growth forms, food web ecology (LA)
Dorothee Ehrich, UiT (dorothee.ehrich@uit.no)	Expert, participant in scientific panel	Rodents, Arctic fox, red fox, food web ecology (LA)
Eva Fuglei, NPI (eva.fuglei@npolar.no)	Expert, participant in scientific panel	Svalbard rock ptarmigan, Arctic fox, food web ecology (HA)
John-Andre Henden, UiT (john-andre.henden@uit.no)	Expert, participant in scientific panel, statistical analyses	Ptarmigan, food web ecology (LA)
Rolf A. Ims, UiT (rolf.ims@uit.no)	Expert, participant in scientific panel, statistical modelling	Predators, rodents, food web ecology (LA)
Ketil Isaksen, MET Norway (ketili@met.no)	Expert, participant in scientific panel	Abiotic climatic indicators, permafrost (HA)
Simon Jakobsson, NINA (simon.jakobsson@nina.no)	Expert, participant in scientific panel	Forest-tundra bird communities (LA)
Jane Uhd Jepsen, NINA (jane.jepsen@nina.no)	Data management, expert, participant in scientific panel	Forest-tundra ecotone, moth outbreaks, food web ecology (LA)
Jesper Madsen, AU (jm@bios.au.dk)	Expert, participant in scientific panel	Birds, pink-footed goose, barnacle goose, breeding phenology, adaptive management (HA)
Jesper B. Mosbacher, NPI (jesper.mosbacher@npolar.no)	Participant in scientific panel	Food web ecology, ungulate (HA)
Ingrid M. G. Paulsen, NPI (ingrid.paulsen@npolar.no)	Participant in scientific panel, data management, analysis, secretariat	-
Virve Ravolainen, NPI (virve.ravolainen@npolar.no)	Expert, participant in scientific panel	Plant biomass, plant growth forms food web ecology (HA)
Eeva Soininen, UIT (eeva.soininen@uit.no)	Expert, participant in scientific panel	Plant biomass, plant growth forms, rodents, food web ecology (LA)
Audun Stien, UiT (audun.stien@uit.no)	Expert, participant in scientific panel	Semi-domestic reindeer, Svalbard reindeer, food web ecology (LA/HA)
Ingunn Tombre, NINA (ingunn.tombre@nina.no)	Expert, participant in scientific panel	Barnacle goose and pink-footed goose (HA)
Ole Einar Tveito, MET Norway (oleet@met.no)	Expert, participant in scientific panel	Abiotic climatic indicators (LA)
Torkild Tveraa, NINA (torkild.tveraa@nina.no)	Expert, participant in scientific panel	Semi-domestic reindeer, food web ecology (LA)
Ole Petter L. Vindstad, UiT (ole.p.vindstad@uit.no)	Expert, participant in scientific panel	Forest-tundra ecotone, insect outbreaks (moth) (LA)
Nigel Yoccoz, UiT (nigel.yoccoz@uit.no)	Data management, expert, participant in scientific panel, statistical modelling	Abiotic climatic indicators, rodents, food web ecology (LA)
Ellen Øseth, NPI (ellen.oseth@npolar.no)	Secretariat	-

Appendix 2: Summary of the PAEC work process of Arctic tundra

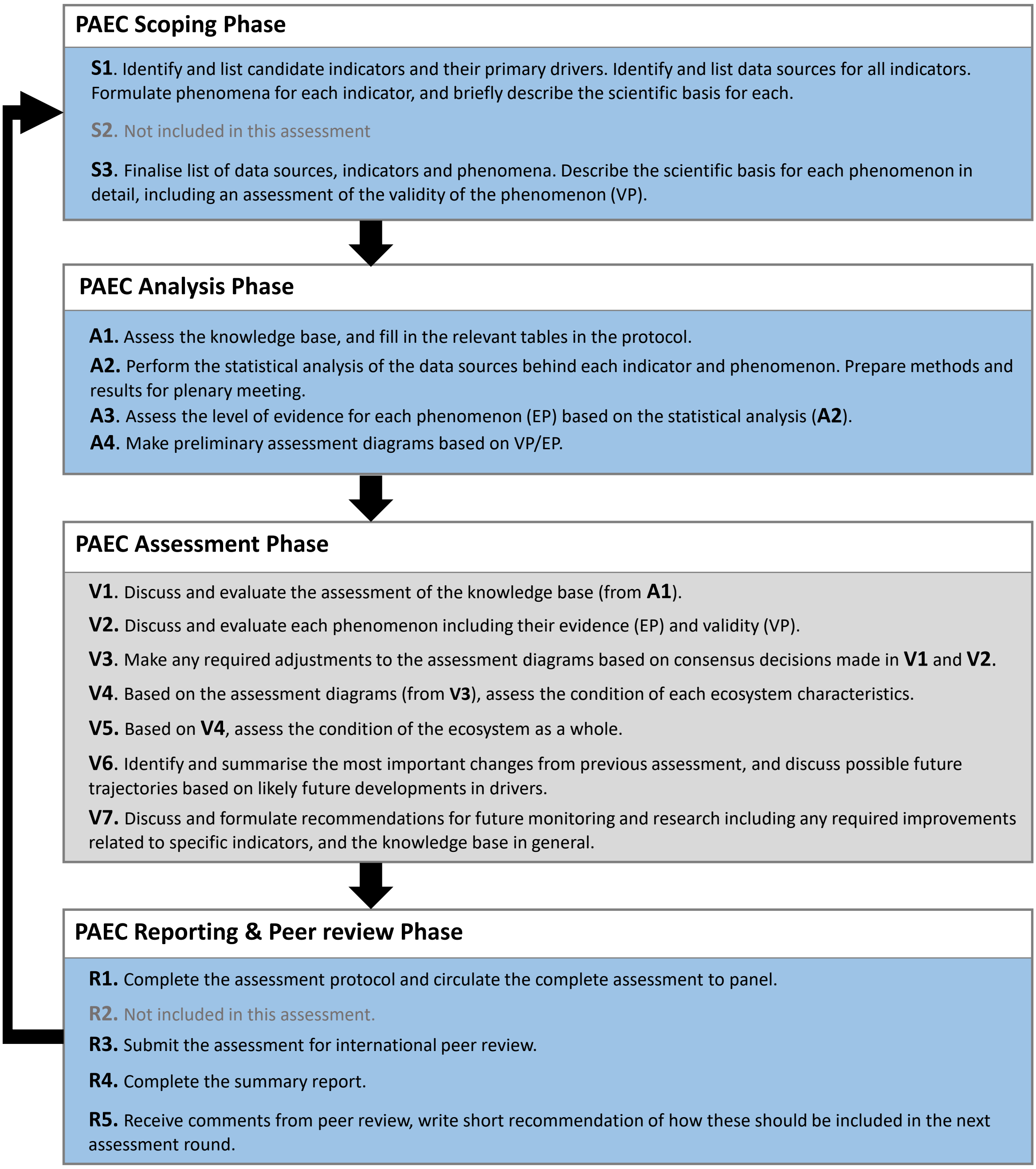
A *Panel-based Assessment of Ecological Condition* (PAEC) consists of four phases (*Scoping, Analysis, Assessment* and *Reporting & Peer review*) summarised in Fig. A1. In the following we briefly summarise how each phase was approached in the assessment of Arctic tundra.

Scoping: Key to this 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. Since a comprehensive pilot assessment had already been completed for Arctic tundra (Jepsen et al. 2019), this phase consisted mostly of a thorough quality check of the list of indicators and associated phenomena formulated during the pilot. Some adjustments were made to the formulation of phenomena as a result of this. New indicators, recommended for inclusion in the pilot, were considered and included if permitted by data availability and resources (see Box 5 and Box 6 for a complete list of indicators). In addition, the set of climatic indicators were harmonised between the two sub-ecosystems, to now represent a close to identical set for Low and High Arctic tundra. A joint meeting involving all members of the panel was not held during this phase, partly due to COVID-19 restrictions. However, we recommend that such a meeting is held during future assessments, to ensure a unified understanding of the phenomena and the subsequent steps in the assessment across the scientific panel.

Analysis: This phase consists of a statistical analysis of the underlying data to permit an assessment of the level of evidence for each phenomenon. During this phase, all the time-series used during the pilot were updated to 2020. If reformulation of phenomena had taken place, the analysis of the relevant indicator was adjusted accordingly. All figures and tables presented as support for the scientific panel were updated and documented by individual R-scripts. The data sources for new indicators were acquired and analysis for these developed. One data source, which received particular attention, was gridded climatic data for Svalbard. The data product used during the pilot is not maintained after 2017 and the Norwegian Meteorological Institute is currently developing a new downscaled product (Haakenstad et al. 2020) which has been thoroughly explored in this project. Since it is not yet an operational product, we chose to show data from both data products for the assessment of High Arctic climatic indicators.

Assessment: This phase consists of a plenary session where the assessment panel scrutinises and assesses the knowledge base underlying the assessment, the condition of the set of ecosystem characteristics covering structural and functional components (biotic and abiotic) of the ecosystem, and finally assesses the condition of the entire ecosystem. The assessment is done in plenary with all members of the scientific panel present. Due to COVID-19 restrictions this had to be done on a digital platform, over two full days. The digital format worked well and is a format which can be considered also for future panel assessments. However, it is important that sufficient time is allocated also to the post-meeting part of the assessment phase, since all decisions made during the meeting must be accurately documented and checked for consistency after the meeting. When inconsistencies in assessments were discovered after the meeting, adjustments were agreed upon with the specific expert(s) involved without calling on the whole panel.

Reporting and peer review: The template for the final assessment report is given by the PAEC protocol (Jepsen et al. 2020). Since a pilot assessment of tundra was available (Jepsen et al. 2019, Appendix 3, in Norwegian), it was used as a starting point. All panel members were involved in writing and commenting on the final assessment report (Pedersen et al. 2021), but a core group of authors were in charge of several additional rounds of review of earlier drafts. An independent international peer review of the final assessment report with the aim of continuous improvements is a fundamental step in PAEC. However, since the Environment Agency has signalled that a joint international review is planned at the end of 2021, a separate peer review of the PAEC assessment of Arctic tundra has not been included in the current work process.



PAEC Scoping Phase

S1. Identify and list candidate indicators and their primary drivers. Identify and list data sources for all indicators. Formulate phenomena for each indicator, and briefly describe the scientific basis for each.

S2. Not included in this assessment

S3. Finalise list of data sources, indicators and phenomena. Describe the scientific basis for each phenomenon in detail, including an assessment of the validity of the phenomenon (VP).

PAEC Analysis Phase

A1. Assess the knowledge base, and fill in the relevant tables in the protocol.

A2. Perform the statistical analysis of the data sources behind each indicator and phenomenon. Prepare methods and results for plenary meeting.

A3. Assess the level of evidence for each phenomenon (EP) based on the statistical analysis (**A2**).

A4. Make preliminary assessment diagrams based on VP/EP.

PAEC Assessment Phase

V1. Discuss and evaluate the assessment of the knowledge base (from **A1**).

V2. Discuss and evaluate each phenomenon including their evidence (EP) and validity (VP).

V3. Make any required adjustments to the assessment diagrams based on consensus decisions made in **V1** and **V2.**

V4. Based on the assessment diagrams (from **V3**), assess the condition of each ecosystem characteristics.

V5. Based on **V4**, assess the condition of the ecosystem as a whole.

V6. Identify and summarise the most important changes from previous assessment, and discuss possible future trajectories based on likely future developments in drivers.

V7. Discuss and formulate recommendations for future monitoring and research including any required improvements related to specific indicators, and the knowledge base in general.

PAEC Reporting & Peer review Phase

R1. Complete the assessment protocol and circulate the complete assessment to panel.

R2. Not included in this assessment.

R3. Submit the assessment for international peer review.

R4. Complete the summary report.

R5. Receive comments from peer review, write short recommendation of how these should be included in the next assessment round.

***Figure A1**. Summary of the four phases of ecosystem condition assessment according to PAEC protocoll (Jepsen et al. 2020), 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, and tasks S2 and R2 were hence not included.*

Appendix 3: List of phenomena in Table 2

Table A3. *Overview of phenomena listed in Table 1 of peer reviewed models analysed to quantify multi-driver effects on components (state variables and ecosystem characteristics of Norwegian Low and High Arctic tundra) and how they encompass different phenomena of the current PAEC assessment of Arctic tundra (Pedersen et al. 2021).*

Ecosystem	Indicator	Phenomenon	
Low Arctic	Maximum vegetation productivity	LP01	Changes in maximum productivity — greening and browning
	Start of growing season	LP02	Earlier start of the growing season
	Rodents versus carnivorous vertebrates	LP06	Decreasing biomass of carnivorous vertebrates relative to rodents
	Mountain birch in forest-tundra	LP14	Sustained reduction of forested area and/or forest density
	Ptarmigan density	LP16	Low and/or decreasing abundance of willow ptarmigan
	Geometrid moth outbreaks	LP17	Invasion of new moth species that establish as outbreak species in the forest-tundra ecotone
	Geometrid moth outbreaks	LP18	Establishment and spread of new moth species in willow shrub tundra far from birch forest
	Semi-domestic reindeer abundance	LP19	Change in abundance of semi-domestic reindeer
	Semi-domestic reindeer calf body mass	LP20	Low or decreasing semi-domestic reindeer calf body mass
	Semi-domestic reindeer calf rate	LP21	Low or decreasing semi-domestic reindeer calf rate
	Large predators	LP23	Low abundance of wolverines and wolves in Low Arctic tundra
	Bioclimatic subzones	LP25	Decreasing total area that meets climate criteria for Low Arctic tundra zones D and E
	Plant communities	LP27	Increased proportion of boreal or woody species at the expense of Arctic or herbaceous species
	Bird communities	LP33	Decreasing abundance and species diversity among open tundra species
	July mean temperature	LP40	Increasing July temperature
High Arctic	Barnacle goose abundance	HP08	Changes in the abundance of barnacle geese
	Svalbard reindeer abundance	HP09	Decrease in the abundance of Svalbard reindeer
	Svalbard reindeer mortality rate	HP10	High or increasing mortality rate of Svalbard reindeer
	Arctic fox abundance	HP12	Decreasing abundance of Arctic fox
	Svalbard rock ptarmigan breeding abundance	HP15	Decreasing abundance of breeding Svalbard rock ptarmigan
	Days with extreme cold	HP16	Decreasing frequency of days with extreme cold
	Winter melt days	HP17	Increasing frequency of winter melt days
	Degree days	HP18	Increasing number of degree days
	July mean temperature	HP21	Increasing July temperature
	Snow cover duration	HP25	Shorter snow season

Appendix 4: List of indicators that are applied in PAEC of Arctic tundra, which have one or more manageable, anthropogenic drivers

Table A4. *Indicators which have one or more manageable, anthropogenic drivers (e.g. hunting, land use, natural resource management) are most relevant for in depth supplementary driver–response analysis to improve our ability to attribute change in the indicators to specific drivers. The table lists all such indicators for both sub-ecosystems addressed in PAEC of Arctic tundra. For each of indicator, any driver–response analysis needs to consider a number of other non-anthropogenic drivers as additional predictors. Given the set of expected drivers, we indicate tentatively whether it is possible to develop driver–response models based on current data. For a number of the indicators, multi-driver–response models are under development, or have already been developed and published, in COAT (see also Table 4 for details of the latter). The last column summarises the status for this work, along with published references.*

				Multi-driver–response analysis	
Indicator [ID]	**Sub-ecosystem**	**Anthropogenic drivers of change in the indicator**	**Other drivers of change in the indicator**	**Possible based on current data**	**Status and references**
Plant biomass [LI03]	Low Arctic tundra	Climate change, reindeer grazing	Site productivity, rodent grazing	Yes	Multi-driver–response analysis ongoing in COAT
Thicket-forming willows [LI11]	Low Arctic tundra	Climate change, reindeer grazing	Site productivity	Yes	Multi-driver–response analysis ongoing in COAT
Mountain birch in forest-tundra [LI13]	Low Arctic tundra	Climate change, reindeer grazing	Site productivity, moth outbreaks	Yes	Multi-driver–response analysis ongoing in COAT
Ptarmigan density [LI15]	Low Arctic tundra	Climate change, hunting	Productivity, rodent abundance, predation, density dependence	Yes	Multi-driver–response analysis ongoing in COAT (Henden et al. 2021a, Henden et al. 2020)
Semi-domestic reindeer abundance [LI17]	Low Arctic tundra	Climate change, natural resource management	Productivity, density dependence	Yes	Multi-driver–response analysis ongoing in COAT
Semi-domestic reindeer calf body mass [LI18]	Low Arctic tundra	Climate change, natural resource management	Productivity, density dependence	Yes	Multi-driver–response analysis ongoing in COAT (Henden et al. (2021b)
Semi-domestic reindeer calf rate [LI19]	Low Arctic tundra	Climate change, natural resource management	Density dependence	Yes	Multi-driver–response analysis ongoing in COAT
Red fox camera index [LI20]	Low Arctic tundra	Climate change, natural resource management	Productivity, reindeer carcasses, other anthropogenic subsidies	Partially	Multi-driver–response analysis ongoing in COAT
Large predators [LI21]	Low Arctic tundra	Natural resource management, hunting	Not relevant	Not relevant	Simple relationship with known drivers. No analysis required
Snowbed encroachment [LI22]	Low Arctic tundra	Climate change, reindeer grazing	Rodent grazing	Yes	Multi-driver–response analysis ongoing in COAT
Plant communities [LI25]	Low Arctic tundra	Climate change	Site productivity, competition	Yes	Multi-driver–response analysis ongoing in COAT
Arctic fox abundance [LI26]	Low Arctic tundra	Climate change, natural resource management	Productivity, competition, rodent abundance	Partially	

Table A4 continued.

				Multi-driver–response analysis	
Indicator [ID]	**Sub-ecosystem**	**Anthropogenic drivers of change in the indicator**	**Other drivers of change in the indicator**	**Possible based on current data**	**Status and references**
Arctic fox camera index [LI28]	Low Arctic tundra	Climate change, natural resource management	Productivity, competition, rodent abundance	Partially	
Pink-footed goose abundance [HI07]	High Arctic tundra	Hunting, climate change, farmland policy	Productivity, density dependence	Yes	Partially developed in Johnson et al. (2020)
Barnacle goose abundance [HI08]	High Arctic tundra	Climate change, farmland policy	Productivity, density dependence, predation	Yes	Multi-driver–response models developed (Layton-Matthews et al. 2020)
Svalbard reindeer abundance [HI09]	High Arctic tundra	Climate change, hunting	Productivity, density dependence	Yes	Multi-driver–response models developed (Hansen et al. 2019a, Hansen et al. 2019b)
Svalbard reindeer mortality rate [HI10]	High Arctic tundra	Climate change, hunting	Density dependence	Yes	Partially developed in Peeters et al. (2017)
Arctic fox abundance [HI12]	High Arctic tundra	Climate change, trapping	Marine subsidies, reindeer carcasses, zoonosis	Yes	Multi-driver–response analysis ongoing in COAT (Nater et al. 2021)
Svalbard rock ptarmigan breeding abundance [HI15]	High Arctic tundra	Climate change, hunting	Productivity, competition, density dependence	Partially [1]	Multi-driver–response analysis ongoing in COAT (Marolla et al. (2021)

[1] Partially is set because the data reflect the breeding abundance of Svalbard rock ptarmigan in spring and not in autumn post reproduction.

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